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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

KNOWLEDGE-BASED SYSTEM ANALYSIS AND CONTROL

ANNUAL REPORT SUBMITTED TO
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ABSTRACT

The focus of the FY86 Program in Knowledge-Based Systems Analysis and Control has been development of an Expert System to aid in the operation of the hundreds of military Technical Control Facilities having responsibility for the worldwide network of DoD dedicated circuits. An initial prototype of the Expert System has been created, embodying a substantial proportion of the knowledge involved, and has resulted in improved understanding of Expert Systems techniques and pitfalls for such problems as well as a clear set of goals for completion of the work.

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I. INTRODUCTION

Dependable communications capabilities may well make the critical difference between success and disaster in military crisis situations, and are essential for effective operation of the DoD in peacetime. Maintaining U.S. military communications assets in a continual state of readiness is therefore an area of major concern. The term "System Control" embraces all the management and control functions that must be performed to maintain peak communications readiness over the lifetime of communications facilities, including such tasks as operating and administering the various networks in the Defense Communication System (DCS), repairing and restoring failed links, and responding to communications emergencies. These functions are coordinated by a hierarchical worldwide System Control organization headquartered at the Defense Communication Agency in Washington.

The basic nature of the System Control structure, little changed in decades (except for gradual modernization of equipment), relies heavily upon the skills and experience of the large number of personnel manning the control facilities. This leads inevitably to a number of problems: (1) chronic shortages of skilled personnel; (2) high training costs; (3) continual increases in equipment sophistication, hence in personnel skill requirements; and (4) continual increases in status and control information flow from modern computerized communications equipment, hence in requirements for personnel to absorb, assess and respond to masses of data.

The goal of the Knowledge-Based Systems Analysis and Control Program at Lincoln Laboratory is to develop solutions for these problems through

application of Machine Intelligence technology. The character of the problems varies with level in the System Control hierarchy, and with the type of facilities being cont.olled: a Tech Control Facility (TCF) handling dedicated circuits is very different from a Defense Switched Network (DSN) control center handling voice traffic flow in a network of computerized digital circuit switches, for example, and yet another set of needs exists at the regional and higher-level control centers. Lincoln's program currently includes an ongoing Expert System development aimed at Tech Control, described in Sections 2 and 3 of this report, and a study of future applications of Machine Intelligence at higher System Control levels, reported in Section 4. In addition to the Tech Control project plans described in Section 5, the FY87 program will include a new DSN control simulation and Expert System design effort which will build upon earlier Lincoln work.

The time scale of the Lincoln program is consistent with a 1990s-era deployment of Machine Intelligence adjuncts to System Control. An engineering model of the Tech Control expert system has been under development throughout FY86, and will be demonstrated in the field in the first half of FY87 (as described in Section 5); completion is expected by the end of FY88, at which time its features and performance can be incorporated into a specification for commercial procurement. The DSN Control Expert System development effort beginning in FY87 will take longer because it embodies some challenging problems, as discussed below, but it is nonetheless reasonable to anticipate commercial procurement within a 5-10 year time frame. Given suitable sponsorship and support, it is also feasible in the same time frame (in view of current technology) to

implement other higher-level System Control concepts as discussed in Section 4.

1.1 Tech Control Problem Definition

The purpose of this subsection is to set the stage for the detailed technical description of the "Expert Tech Controller" in Section 2. We first describe the Tech Control Facility (TCF) problem domain and the way it is presently handled by skilled staff personnel; we show the problem's appropriateness as a classic near-term application of Expert System techniques; and we then describe the functions that the objective Expert System will perform for its human operators.

Tech Control deals with full-time dedicated circuits, and effectively resides at the foundation layer of the System Control hierarchy. There are some 61,000 dedicated circuits in the worldwide DCS; many of them furnish full-time connectivity for specific critical users, while others (especially overseas) provide transmission services for various networks of the DCS. Each dedicated circuit is served by a Tech Control Facility at each end, and generally by one or more additional TCFs at intermediate points en route. There are about 400 TCFs, many of them handling up to 1,000 circuits or more; most are overseas, where the U.S. military tends to own and manage circuits directly. In CONUS, by contrast, most military dedicated circuits are provided and serviced by commercial vendors.

A Tech Control Facility typically has circuits ranging from 75-baud teletype links to broadband microwave carriers. The transmission facilities typically include a wide variety of media installed over a period of years, from old unconditioned telephone lines, to analog and digital multiplexed

facilities, to modern fiber optics, microwave and satellite links. Similarly, the equipment within a TCF ranges in age and complexity from 1950s-era analog carrier gear to the latest microprocessor-controlled test and multiplexing equipment.

The primary duties of the staff at a TCF (typically in three shifts around the clock, totalling 60 or more personnel at the busier sites) include: (1) rapid restoral of service whenever outages occur, (2) routine circuit test and maintenance, and (3) planning and implementation of circuit changes and additions pursuant to DCA orders, in response to changing user requirements. Category (1) is the most critical: each circuit has a "restoral priority", depending on the mission it serves. The most important circuits have spare facilities that can be activated in the event of failure, or can pre-empt facilities in use by circuits of lesser priority, while others are "logged out" until repairs are completed. In any case, the Tech Controllers proceed as rapidly as possible to do "fault isolation" (i.e., to identify the failed subsystem) and arrange for repairs. During this process they prepare DD Form 1443, an outage report detailing the history of the problem; this report is ultimately transmitted up the System Control hierarchy.

The second category of Tech Control duties is typically tedious and slow, involving repetitive tests, measurements and record-keeping on large numbers of circuits. Some automation has been introduced, but human supervision is required in managing and interpreting the results. Typically these duties are carried out by the more junior staff, with skilled instruction and assistance as necessary.

A TCF may have several people assigned full-time to the third category of duties, since circuit configuration changes occur often enough that there may typically be several tens of them in the process of planning and preparation. The process begins when a user agency submits a "Telecommunications Service Request" (TSR) to the DCA stating a requirement for a circuit change or addition, and the DCA responds by selecting the routing and facilities to be installed or re-allocated to meet the requirement. These are specified in a highly formatted "Telecommunications Service Order" (TSO) sent to all TCFs affected by the change; each of the latter carries out detailed planning and preparation of the necessary in-house changes, and all parties activate the new circuit on a pre-determined date. As part of this process, each TCF prepares a DD Form 1441 card for the new circuit, containing dozens of items of information about it, which becomes a part of the master card file that constitutes the data base of the TCF.

Pervading all of these TCF activities are manpower and training problems of major proportions. TCFs are staffed by active duty military personnel, most of whom are relatively young and inexperienced: as soon as personnel acquire telecommunications skills, they are eagerly sought by civilian companies offering good pay and stable jobs. Besides lacking required skills (the training schools are very basic), new arrivals at a TCF face an enormous task of learning the configuration and characteristics of the circuits and equipment unique to that site. By the time they achieve reasonable familiarity, it is likely that they will be transferred (under normal military rotation policy) to another duty station.

The result of these pressures is that only a fraction of the personnel at a typical TCF have the skills and knowledge necessary to operate it. For example, at the 2045th Information Systems Group at Andrews Air Force Base (discussed in Section 2 as the target environment for the Expert Tech Controller development), there is a complement of 62 to 65 personnel, of whom 50 are trainees. Moreover, because of military budget and manpower constraints it is often true that a TCF has fewer personnel than its authorized complement.

The Tech Controller's expertise is complex and extensive, yet ultimately describable in terms of reasoning and inference drawing upon factual knowledge. This is precisely the domain of modern Expert System development, in which Knowledge Engineers capture the expertise of skilled practitioners in the target environment through extended interaction, translating it into a software system capable of performance approaching that of the experts. A suitable Expert System can ameliorate the above-described concerns in Tech Control in four ways: (1) guiding novices through the solution of difficult problems; (2) easing the shortage of skilled manpower, by allowing discretionary use of less-qualified personnel in higher-level positions; (3) preserving a "corporate memory" of circuit problems rare enough that they may never have been encountered by personnel currently assigned; and (4) easing the training burden for senior personnel. Interestingly, while the first three of these benefits have perhaps greater long-term potential, the fourth aroused the most enthusiasm among senior Tech Controllers consulted during the formative stages of the Lincoln program. Instead of spending three-fourths of their time

conducting training sessions with books, paper and pencil, senior NCOs could look in occasionally while the Expert System guides trainees through realistic fault isolation and problem-solving exercises.

To be more explicit, the function and operation of the "Expert Tech Controller" (referred to as "ETC" for brevity) under development at Lincoln Laboratory will appear to the users as follows. ETC is implemented in a small Symbolics 3645 computer, with a high-resolution video terminal and keyboard, which will remain quiescent in a TCF until invoked to solve a problem. When an outage occurs in one of the circuits served by the TCF, Tech Controllers currently learn of it by means of a fault alarm light or signal from the equipment, or (more typically) through a complaint called in by a user of the circuit. When ETC is to be used to diagnose a fault, it will be invoked by a human operator who enters the outage symptoms via keyboard and menu/mouse facilities. ETC begins the fault diagnosis process by calling up all the information in its data base on circuits that may be relevant to the problem; this reflects the standard beginning step by human experts, which is to go to the 1441 card file and pull all the cards that may be involved. (In fact, ETC's data base is created by effectively entering 1441 card images, by means of user-friendly editing facilities.) ETC then displays a graphic image representing a diagram of the failed circuit and related facilities; this is analogous to the hand-drawn circuit diagrams currently found on 1441 cards. (The graphics are not used by ETC in the diagnosis, but are provided for the operator's convenience in tracing and understanding the logic.)

ETC then pursues a fault isolation strategy reflecting the approach that would be taken by a skilled human technician in similiar circumstances. A dialogue is conducted with the operator via terminal and keyboard, requesting status and parameter information (such as signal presence/absence, level, quality) at particular points of interest at the current stage of diagnosis. Finally ETC presents a conclusion as to the faulty component, together with a selection of appropriate corrective actions for the human operators to choose from.

ETC serves operator interest and training objectives by highlighting the region of the graphics display which is the current focus of attention during a diagnostic session and by providing explanations (on request) of the logic of the question currently being asked. An example of a training feature which is readily implementable in ETC (though not yet in place) would be a special instruction mode in which a student operator is required to predict the next question in the dialogue before ETC proceeds, and records are kept of the student's performance. Another valuable training feature inherently present in the ETC concept is the ability to load ETCs at a stateside service school with the data bases of overseas TCFs, as a means of giving students a long head start in familiarization with the specific sites to which they are about to be assigned.

1.2 Summary of Activities

The Program began with study and architecture definition efforts prior to FY86, as noted earlier. In October 1985 specific arrangements were made with the commanding officer of the 2045th ISG (at Andrews AFB) to participate with Lincoln Laboratory in the development of the Tech Control

expert system, by providing the necessary expert knowledge. Choices were made by Lincoln as to hardware and software environments for the initial implementation (the "Mark I Expert Tech Controller"): the Symbolics 3640 computer with its native ZetaLISP language, hosting an expert system development shell known as ART (for Automated Reasoning Tool), purchased from Inference Corp.

A series of nine intensive Knowledge Engineering interactions took place through the fiscal year, four at the Andrews Tech Control Facility and five at Lincoln Laboratory. Fault diagnosis techniques were successively described, implemented and refined in this process. Dates and locations were:

3-4 December 1984	(Andrews)
22-23 January 1986	(Andrews)
1-2 April 1986	(Lincoln)
1 May 1986	(Andrews)
15-16 May 1986	(Lincoln)
17-18 June 1986	(Andrews)
4-5 August 1986	(Lincoln)
10-11 September 1986	(Lincoln)
23-23 September 1986	(Lincoln)

The 15-16 May session was exceptional, in that it included a critical review of the system philosphy and current capabilities by senior representatives from the Scott AFB headquarters for Air Force Tech Control operations worldwide. The 23-25 September session was concurrent with a Program Review conducted at Lincoln Laboratory for the sponsors, and

included another system evaluation by operational Tech Control personnel; a detailed demonstration of ETC for the review attendees; and a series of technical presentations by Lincoln engineers on the program, followed by a discussion period. The general tenor of the visitors' reactions was positive as to the form, objectives and current status of the system. They made technical comments and recommendations which are being addressed in the FY87 program.

Early in the year, contacts were established with the TCJ SPO at the Air Force Electronic Systems Division, which is managing the procurement of the CNCE (Communications Nodal Control Element), a transportable tactical Tech Control facility for battlefield applications. The CNCE contains electronically-controlled patching and testing equipment, and its operators carry out all their Tech Control functions by means of software in an AN/UYK-20 computer. As such, the CNCE is very well suited for a future Expert System implementation which could not only guide the operator through the solution of problems but also directly implement the chosen remedial actions. Lincoln Laboratory representatives were invited by the TCJ SPO to attend certain project management meetings at the CNCE contractor's plant (Martin Marietta), where contractor personnel were briefed on the Expert Tech Controller and consulted as to ideas and mechanisms for a possible future Expert System for the CNCE.

The following section of this report gives a description of the current Expert Tech Controller implementation. Section 3 describes the lessons learned in the project to date about expert system implementation

in a communications network environment. Section 4 gives the results of a study carried out during the year on architectures for a simulation-based testbed for System Control techniques. Section 5 discusses plans for FY87 work on the project.

2. EXPERT TECH CONTROLLER SYSTEM DESCRIPTION

The ETC system we are developing is intended to demonstrate the potential for machine intelligence techniques in tech control. We believe that there are seven task areas in which such techniques could have value in future tech control facilities. Table I lists these task areas. The order of the tasks in the list reflects our understanding of the relative importance of the tasks to the tech control mission. The primary task of a TCF is to restore service for its communication users in the event of an outage caused by equipment failure, weather, hostile action, or whatever. However, it is usually the case that some fault isolation work must first be carried out before the location for the patch can be determined. Thus the fault isolation and service restoration tasks are closely coupled. The third task, outage reporting, is also closely tied to fault isolation and restoration, since TCFs are required to report outages and the restoration actions taken in a timely fashion.

The fourth task, database management, is an off-line task as carried out in current TCFs. The term "database" is used by the tech controllers to refer to a particular looseleaf notebook of data about the circuits passing through the TCF. This data is updated automatically by mailings of new pages from DCA headquarters. Thus, the maintenance of that particular

TABLE I
ETC SYSTEM TASKS

1	Service restoration
2	Fault isolation
3	Outage reporting
4	Database management
5	Routine testing
6	Training
7	New facility planning

notebook is not a significant task. We use the term "database", however, to refer to the total body of information used and maintained by the TCF staff. This consists of a file of circuit data cards called "1441 cards" that are used together with wall charts and equipment labels in fault isolation and restoration work. In addition, a TCF has file cabinets full of routine circuit test data, trouble histories, cable charts, floor plan layouts, etc. that are used as needed. In order for the ETC system to handle the first three tasks, much of this total database must be made available to the computer. The realization of a computerized data base will have the additional benefit of reducing the effort required for a TCF to keep its da abase up-to-date and correct. Thus, the fourth task, database management has a dual function in the ETC system.

The fifth task, routine testing, provides the TCF with information on the quality of the service that the circuits are providing to the users. By monitoring circuit quality on a periodic basis, the controller can detect deteriorating circuit conditions and in some cases prevent any outage by taking corrective action before actual failure occurs. The ETC system should be able to help in this area with the scheduling of tests, the recording of data, and the analysis of trends in the data that could indicate incipient trouble. Data from routine tests can also be used to advantage in the fault isolation process by providing measurement data for comparison purposes. Trend analysis can help in suggesting which of a set of otherwise equally likely tests to try next.

The last two tasks, training and new facility planning, can be viewed either as fringe benefits from the ETC system or major goals in

themselves. The existence of the database and the fault isolation and service restoration capabilities allow the ETC to be used for training purposes with little additional development. An instructor and trainee can use the system to follow a wide variety of trouble scenarios without risk to any actual communication capabilities. With augmentation, ETC could simulate faults for the trainee to diagnose and could record his handling of problems for later analysis by an instructor.

The database by itself can offer some help with new facility planning by providing the controller with information about the availability of resources such as test jacks, rack space, cables, etc. in the TCF. With augmentation, ETC could be programmed to work out a detailed plan for the installation of new equipment or reorganization of existing equipment, picking jack locations, making wiring schedules, etc. As installation progressed, the database would automatically be kept up-to-date.

During FY86 we have initiated implementation work in the first four areas with the greatest effort going into fault isolation because that area is the one with the most potential for machine intelligence techniques. We have done nothing yet to support routine testing, to enhance the system's potential as a training aid, or to help with new facility planning. In FY87 we expect to start work on routine testing support and to plan for some training enhancements, but we do not expect to undertake any activity in the new facility planning task area in the next year.

In future tech control centers we anticipate that direct connections will exist between the communication equipment in the center and the computer supporting the intelligent control functions. With such

connections the control computer will have direct access to fault indications and will be able to initiate tests and circuit patches without human intervention. Human involvement in such a center would be primarily supervisory in nature, and the total number of people needed at a center would be significantly reduced relative to the current situation where many people are needed to operate a large facility such as the one at Andrews AFB.

The programming environment being used for the development of ETC runs on a Symbolics 3645, a sophisticated Artificial Intelligence workstation. This environment provides the machine's native programming language, LISP, its object-oriented programming tool, Flavors, and its many other built-in system development, user interface, and debugging aids.

We have augmented this environment with a commercial state-of- the art expert system building tool called ART that is a product of Inference Corporation. ART provides rule-based programming facilities which include backward and forward chaining inference mechanisms, a frame-based knowledge representation, hypothetical reasoning, pattern matching, and a number of its own program development, user interface, and debugging tools.

Our experience to date suggests that this environment will provide the functionality needed to handle the complexity of the ETC problem domain. In particular we believe that the frame-based knowledge representation coupled with the procedural and rule based processing, is powerful enough to represent the wide variety of information necessary. Currently this information includes circuit topologies, physical locations of devices, measurements (currently obtained by the user and eventually to be obtained

automatically), rules and heuristics from experts, book and manual diagnostic procedures, and the structures necessary for the graphical user interface.

2.1 Fault Diagnosis and Circuit Restoration

Fault diagnosis is the process of localizing the failed element in a malfunctioning circuit. The Tech Controller's primary goal is to restore service to the end users of the circuit, within a time interval of a few minutes or longer, depending on the "Restoration Priority" of the circuit. Typically he will pursue fault diagnosis to narrow the problem area just enough to identify the right backup facilities or spare equipment to switch in, to restore service on the circuit. After service has been restored, a finer-grained diagnosis we call "post-restoration fault isolation" can be used to identify the cause of the problem, whereupon a repair call can be initiated. This section of the report will describe in detail the processes of fault diagnosis, circuit restoration, and post-restoration fault isolation.

2.1.1 Problem Dimensions

Fault diagnosis, circuit restoration, and post-restoration fault isolation are affected by several factors. Many of these factors interact, creating a very complex problem in terms of both processing strategies and database organization necessary for successful implementation.

We would like ETC to be able to isolate the causes of the various kinds of problems (no signal, excessive retransmissions, etc.) that can occur on many types of circuits (voice, digital, etc.) carried by a wide variety of types of links between Tech Control Facilities (e.g., satellite

channels, landlines, HF radio). This broad problem domain involves a complex set of devices that must be represented in ETC's detailed knowledge base. Compounding these difficulties is the fact that budget limitations over the years have resulted in TCFs having a wide range of device models, manufacturers, vintages, and levels of sophistication.

Another complex aspect of the problem domain is coordination between diagnosis and circuit restoration. The system is generally capable of finer-grained fault isolation than may be necessary, or even desirable, prior to performing circuit restoration. ETC must be able to recognize the earliest point at which appropriate spare facilities are available for restoration of service on the circuit. This point varies with not only the inventory of spare devices but also the connectivity of trunks between Tech Control Facilities and the relative ease of the substitution process for particular devices.

Further difficulties result from the fact that circuits typically pass through several Tech Control Facilities between the end users. A distributed problem solving mechanism is therefore needed, providing for communication with either expert systems or humans at other TCFs. To assure effective interaction, protocols for this process must be established and enforced.

This multiplicity of dimensions creates a very complex problem space requiring sophisticated processing mechanisms and database management techniques. The architecture described here appears to meet these requirements.

2.1.2 Fault Diagnosis System Architecture

A high level of expertise is necessary to perform effective fault diagnosis on a network of this magnitude. Based on many knowledge engineering sessions, we quickly concluded that a skilled tech controller is well-informed about a number of strategies for fault diagnosis and about the rationale for selecting among them. Reflecting this general approach used by human experts, we have developed a modular, strategy-oriented Expert System to perform the fault diagnosis functions. This system integrates the efficient procedural facilities of LISP and the flexible rule-based facilities provided by ART.

Figure 1 shows the modular organization of the control mechanism for the fault isolation mechanisms of the expert system. The top two boxes represent a sequential series of information-gathering steps done at the beginning of each diagnosis. The third box represents the process carried out when necessary to convert the database representation of the circuit in question to a form more easily manipulated by the rest of the system. The fourth box, considering all the circuit and complaint information collected thus far, determines which fault isolation strategies in the repertoire of the system may be applicable to the current problem. This list of applicable strategies is passed to the strategy control module. The strategy control function initiates each of these candidates in turn until one of them isolates the cause of the problem to the level of a subsystem that can be bypassed by other equipment; at this point the strategy accesses the Circuit Restoration facilities to be described below.

The large box in the bottom center of Fig. 1 represents the full repertoire of fault isolation strategies available to the system. A new

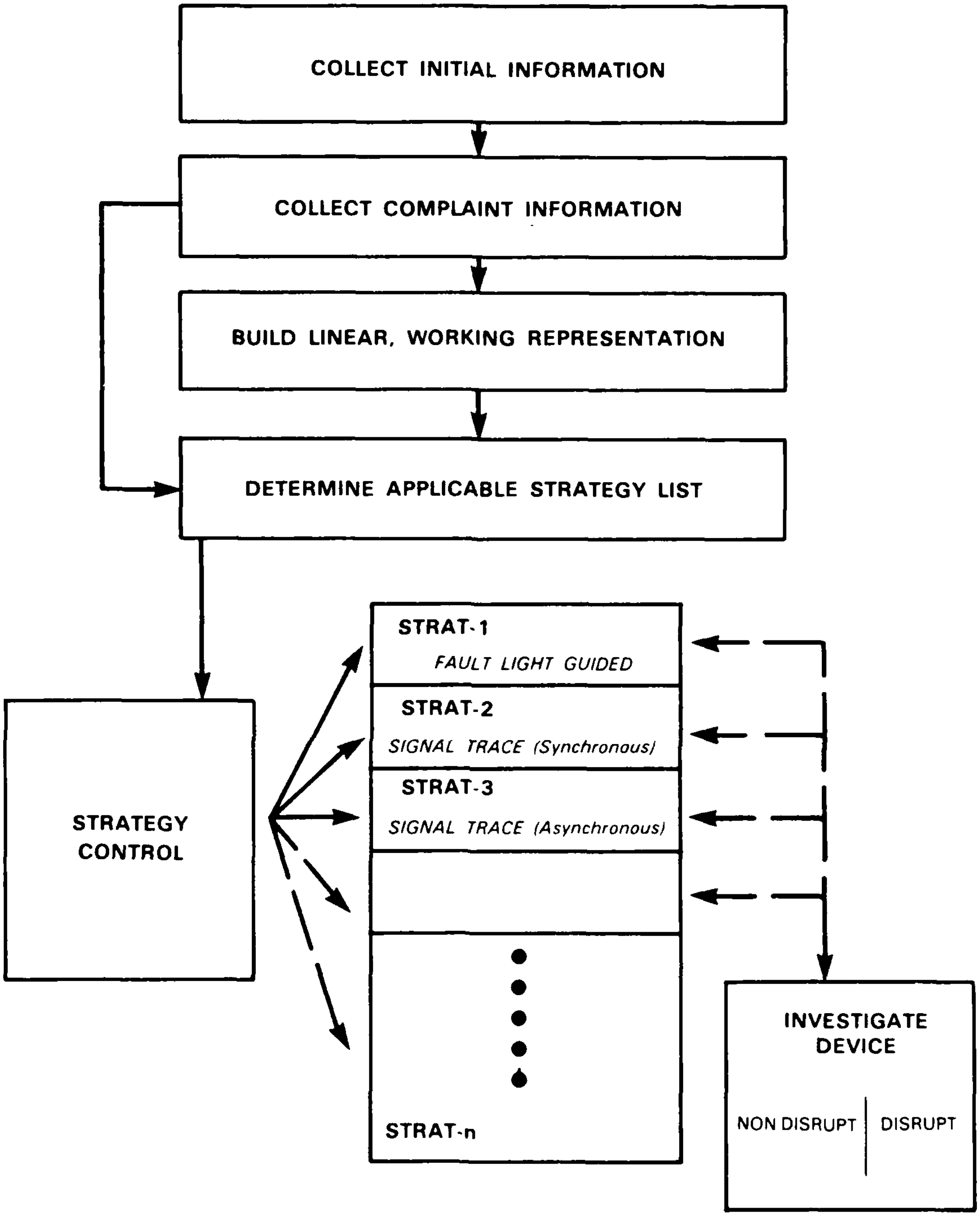

Figure 1. Fault isolation control.

strategy can be added by simply writing the necessary code and rules, then informing the Applicable Strategy List generator as to conditions under which the new strategy may be applicable. The Investigate Device module at the lower right in Fig. 1 contains diagnostic expertise on the individual communications devices in the knowledge base of the system. Note that all fault diagnosis strategies have access to this expertise.

2.1.3 Level of Expertise

The sophistication of the current fault diagnosis and circuit restoration system can best be described by stating the extent of four factors: the types of circuits and types of complaints the system can handle; the communications devices that have been implemented; the fault diagnosis strategies that are in the system's repertoire; and the types of circuit restoration the system can currently perform. From these factors one can infer the types of problems that can be diagnosed and the types of circuits on which the system can do fault isolation.

2.1.3.1 Circuit and Complaint Types

Our long-range goal is the capability to do fault isolation on all circuit types of interest to TCFs. Currently the system is limited to digital circuits; in the near future we plan to add the capability to isolate faults on analog voice circuits. Many circuits of both types pass through the Andrews TCF, and will be used to refine the fault isolation procedures being developed.

Another limit of the system at present is that it can handle only one type of complaint, namely the "no signal" case in which the signal has been lost completely somewhere in the path of the circuit. Development is currently underway on algorithms to deal with other types of complaints.

2.1.3.2 Device Implementation

Fault diagnosis software has been developed for a number of devices and circuit types. The work focused initially on circuit F142, a weather data reporting circuit passing through the Andrews TCF which links computers at Croughton, England and F142 is a high-speed synchronous circuit using three major devices at Andrews, namely:

(1) AT&T-2096 - Modem / Multiplexer

(2) CITAG - Alarm Group / Buffer

(3) HSTDM - High Speed Modem / Multiplexer

The term "implementation of a device" means providing the Expert System with the ability to diagnose faults caused by malfunction of the device. For each device that has been implemented in its repertoire, the system can conduct a mouse-oriented, interactive session in which the user is guided step-by-step through diagnostic procedures on the device. The user's answers are analyzed by the system to guide further questioning. Eventually the system will determine whether the device in question is faulty, and so inform the user. These interactions attempt to use "natural" diagnostic strategies reflecting a combination of the suggestions of skilled human tech controllers and the technical manuals for the devices. We have observed that the human experts tend to stop the diagnosis process as soon as they know what equipment substitutions to make in order to restore service, while blindly following the manuals would lead far beyond that point.

Three other devices were then implemented, namely:

(1) OMNI-MUX-160 - Multiplexer

(2) LSTDM - Multiplexer

(3) VFCT - Modem / Multiplexer

We have also added the capability to isolate failures that occur in the transmission medium carrying the signal between TCFs. The normal outcome of this process is to alternate-route the signal through another path or medium, and to call the appropriate service contractor to repair the failure.

The combination of these six devices and the ability to isolate faults between TCFs has allowed a number of circuits to be installed in the knowledge base of the Expert System. These circuits include high-speed synchronous circuits such as F142, as well as low-speed teletype lines. This set of installed circuits and devices amounts to a very complete environment for development and testing of rules and procedures for fault diagnosis, circuit restoration, and graphics. This test environment is currently being used to develop and refine a system to handle to the complaints and circuit types described above, and encompasses a substantial fraction of the circuits that pass through the Andrews TCF.

2.1.3.3 Fault Isolation Strategies

Discussions with the Tech Controllers at Andrews have led to identification and implementation of three fault isolation strategies relevant to high-speed synchronous circuits and low-speed TTY lines. The first of these is an alarm-guided mechanism. Through interaction with the user (or, in the future, by polling a set of alarm repeater lines) the system learns the current state of all indicator lamps and alarms on the devices in the circuit. These alarms are then analyzed by the system, based on its knowledge of the nature and causes of alarms, to guide the fault isolation process.

If there are no alarm indications, or if the first strategy is unsuccessful in isolating the cause of the fault, two other strategies may be used. Both implement a signal-tracing mechanism, one for high-speed synchronous circuits and one for low-speed TTY lines. This kind of strategy seems to be the one chosen most often by tech controllers. It makes use of test points where the signal can be observed without disrupting service, to identify the device or devices that may be causing the problem. Once a device is identified as a potential problem, more extensive device-specific questioning can proceed to determine whether it is actually at fault.

It is expected that additional strategies will be implemented throughout the development of the system. For example, a fourth strategy (for locating problems on trunks) and a fifth (to handle excessive-retransmission problems) are currently under development.

2.1.3.4 Circuit Restoration

The tech controller's top priority when working with a circuit outage is to restore service to the users of the circuit as quickly as possible. This could include repairing or adjusting devices on the current path of the circuit, or rerouting part or all of the circuit path through alternate channels, devices, trunks, or tech control facilities. It is important that the Expert System place a similarly high priority on circuit restoration.

Outages that require alternate routing create a particularly interesting type of problem. We have been creating knowledge representations and alternate routing strategies that will guide the tech

controller to use the most effective alternate routes and restore service as quickly as possible. Some circuits use devices like 2096s and HSTDMs which often have full-time spare facilities available at the flick of a switch; rerouting these circuits can be a straightforward problem. Rerouting circuits that use devices such as the VFCTs or LSTDMs can be more complex. For example, the Andrews TCF has 32 VFCTs with a number of spares. A circuit outage caused by a bad channel on one VFCT involves locating the best way to reroute the single effected circuit. The preferred solution according to current practice is the first of the following three procedures that is possible:

(1) Reroute the circuit on a working spare channel on the same VFCT.

(2) Reroute the circuit through another VFCT with the same destination.

(3) Find a solution in a card file built up over the years on how to get certain important circuits from one place to another.

Along with being able to restore service by substitution of complete devices, trunks or channels, as described above, the Expert System can suggest other possible routes selected from the equivalent of the card file. The system modifies the graphics displays to show alternate routing mechanisms as they are implemented. Details of device and trunk patches in use, as well as spare devices temporarily in use for test purposes, are shown on the displays. This helps the user to better visualize the dynamics of the circuit configuration during and after fault diagnosis.

2.1.4 Demonstration Scenario

The best way to understand exactly what the Expert System does is to actually see it work. Since that is impossible in a report, a realistic

scenario will be described using copies of a number of terminal screen displays. The purpose of this section is to give the reader a general feel for the problem-solving process, along with an introduction to the user interface and graphics capabilities of the system.

The scenario involves a circuit between Bermuda and Carswell, Texas which is designated 7DUM. Each interaction between the user and the Expert System begins with a question to determine what the user wants to do (Fig. 2). In this case we selected "Diagnose Fault". It should be noted that nearly all the questions asked of the user are mouse-sensitive menus or items; this makes the system extremely easy to learn and use.

The next question (Fig. 3) asks for the type of complaint that initiated the fault diagnosis process. In this case we are assuming that a user complaint was received. Another interaction elicits the designation of the circuit to be diagnosed (7DUM), and the system consults its database and produces three important graphic displays. The first (Fig. 4) is an exact replica of the DD Form 1441 for this circuit that is currently in the physical card file at the Andrews TCF; this is the source that the tech controllers now use to obtain most of the circuit information. The other two graphic displays, shown in Fig. 5(a), are an overall circuit diagram of the source, destination and intermediate facilities (bottom) and a detailed diagram of the devices in the circuit path within the Andrews TCF (top). Close examination of the upper graphic in Fig. 5(a) shows the system representation for three different multiplexers. This scenario assumes that the fault is in the VFCT on the right. The small numbers to the left of this box indicate all the circuits using it, and sharing trunk 6J04

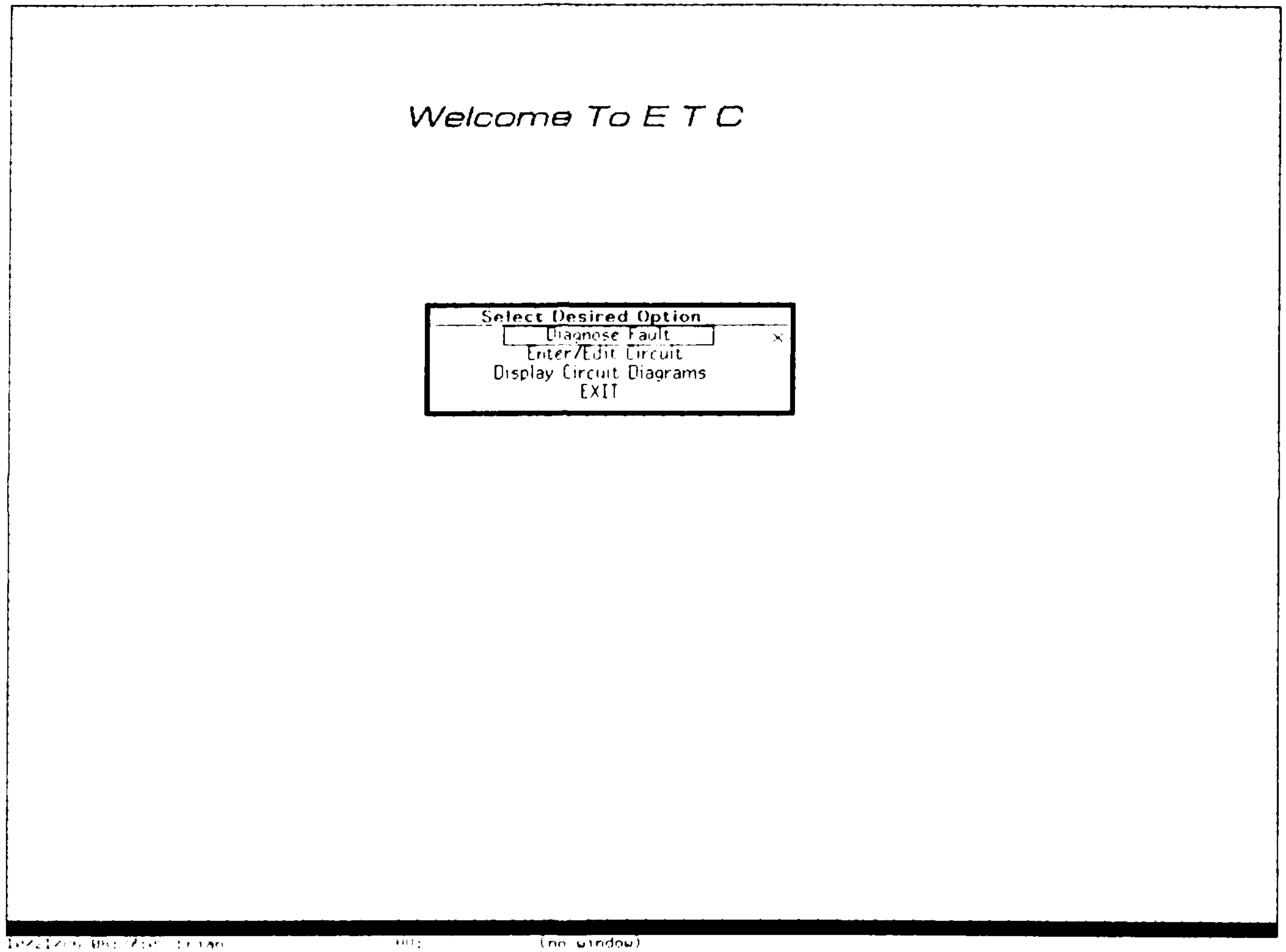

Figure 2. ETC main menu.

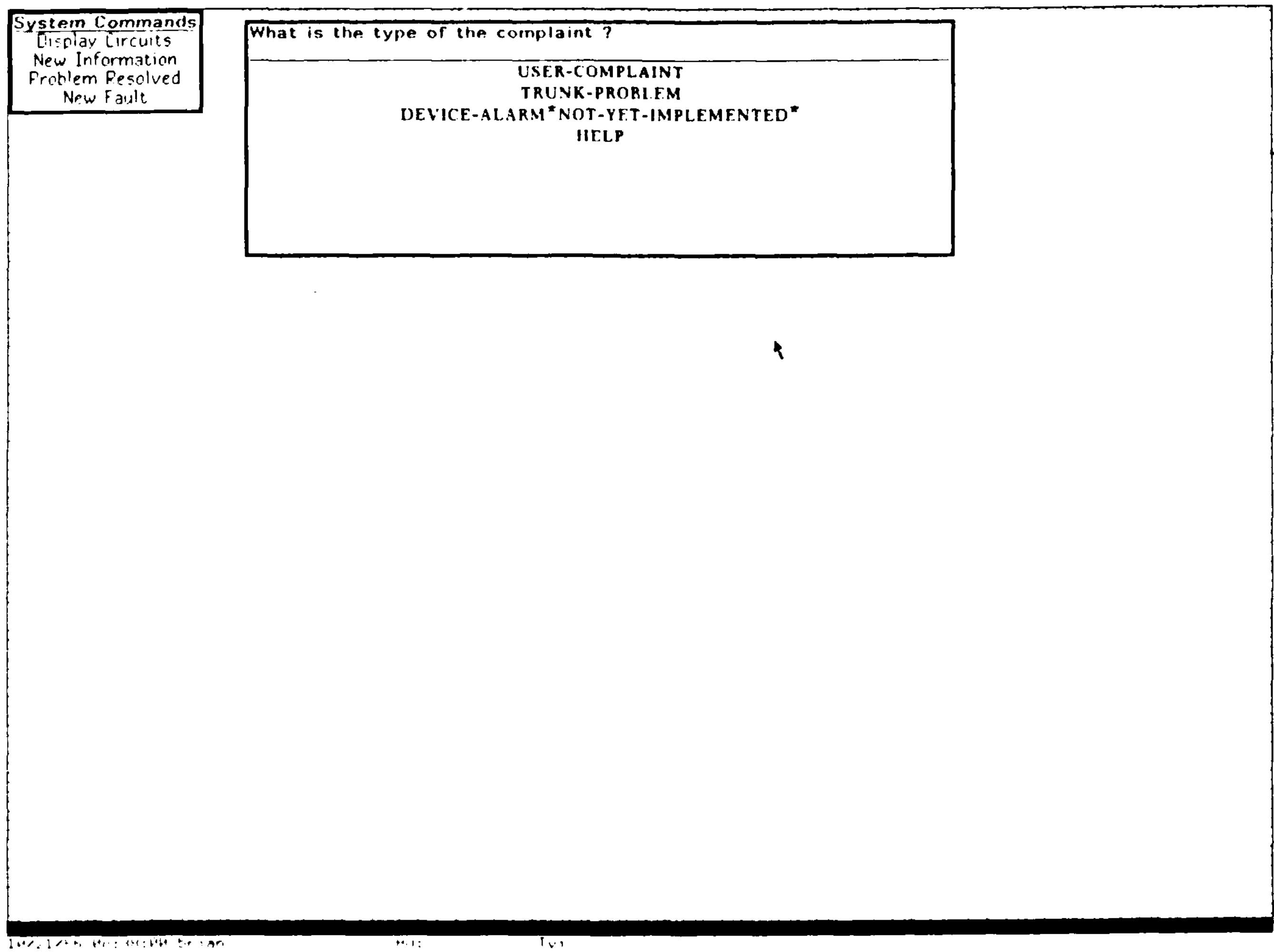

Figure 3. Problem type menu.

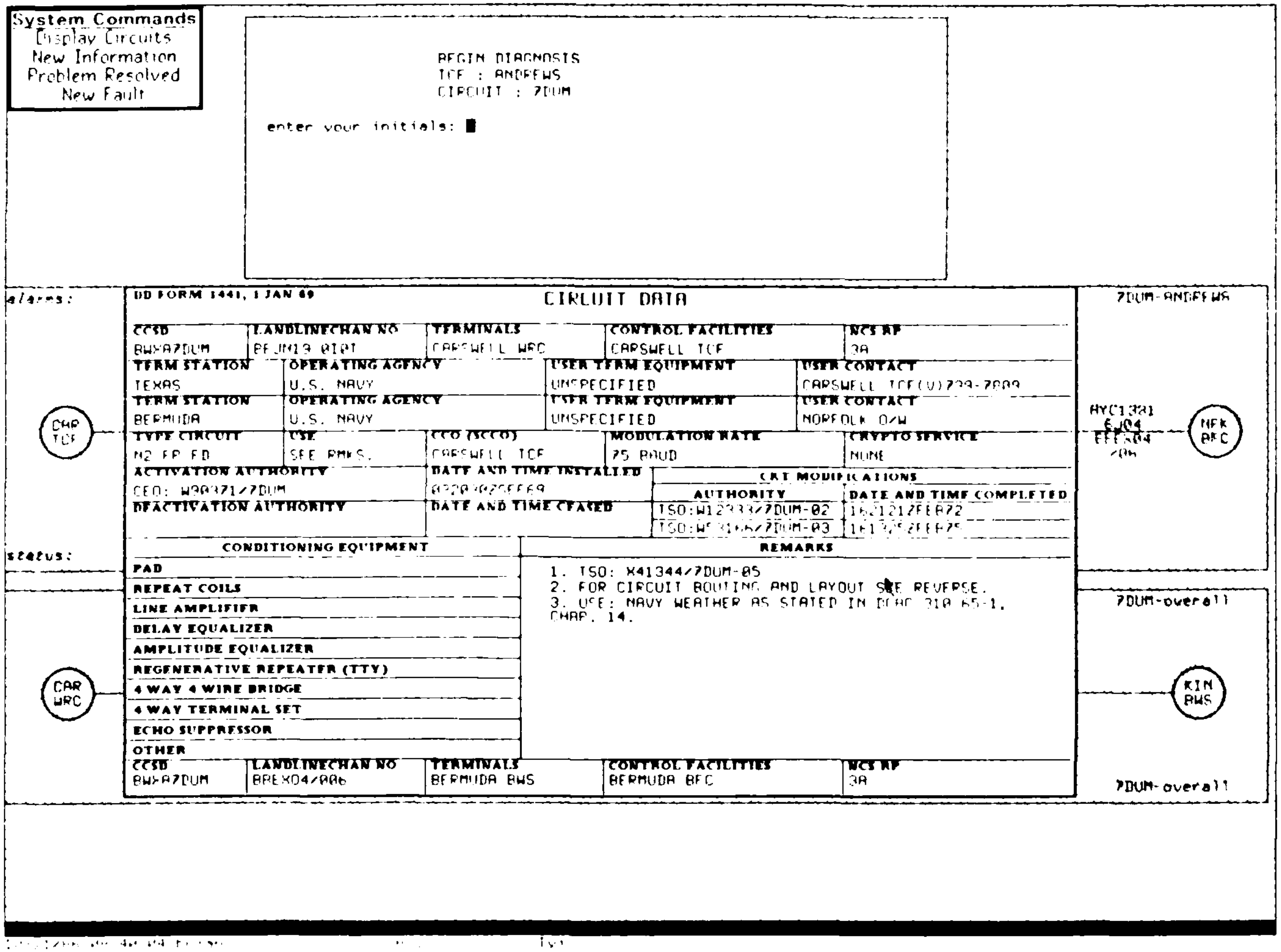

Figure 4. 1441 display.

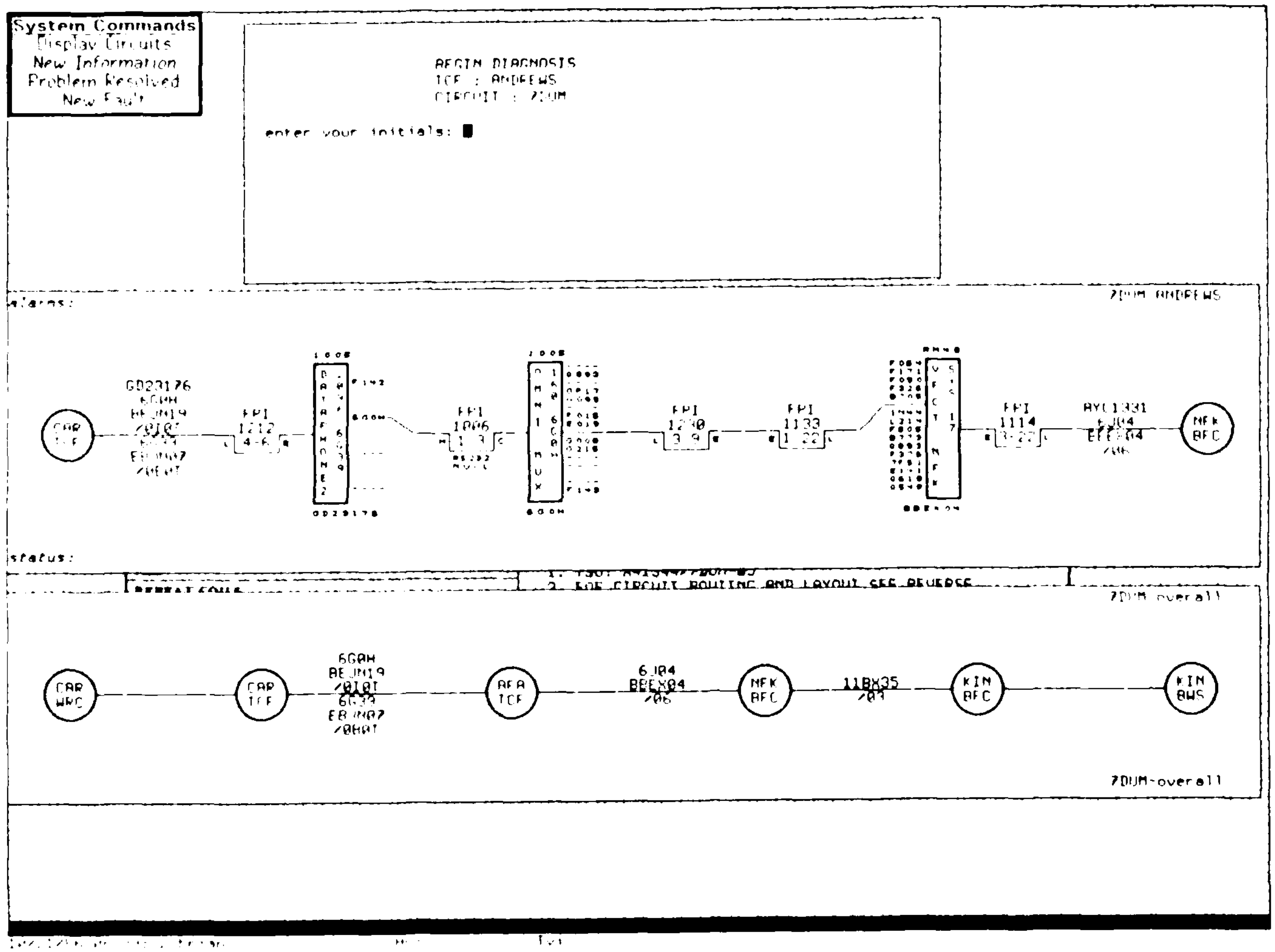

Figure 5(a). Circuit diagram display.

exiting toward the Norfolk TCF on the right. Multiplexer inputs labeled with a dashed line instead of a number indicate spare channels, as shown on the ATT-2096 and the OMNI-MUX-160 in the display. Because of the larger size and high resolution of the actual Symbolics terminal screen, these features are more easily interpreted than the screen images shown here would indicate. These circuit diagrams are generated dynamically from the database, and contain much more information than tech controllers currently show in hand-drawn circuit diagrams on the backs of 1441 cards.

2.1.4.1 The Fault

The fault that is assumed for the purposes of this sample scenario is a bad receive channel on the VFCT in Fig. 5(a). Figure 5(b) shows a replica of this diagram that has been hand marked to show all the consequences of this fault that could be observed by the tech controller. In order to be able to give logical and consistent replies to the Expert System in the course of the diagnosis, this information has to be worked out in advance, as follows. Carswell would be receiving a constant mark instead of the expected continual keying. The only device having alarm indicators on this circuit is the ATT-2096. Since the signal for 7DUM at the ATT-2096 is riding trunk 6GOH, which also carries traffic for other circuits, the loss of just 7DUM will not cause any alarm conditions on the device. Because of the direction and nature of the assumed fault, signals are not present at jacks FPI-1133-1-22 and FPI-1230-3-9. Since the problem is with only one receive channel of the VFCT it can be assumed that a signal is being sent from NFK-BFC (the Norfolk TCF) and that all other outputs from the VFCT are present.

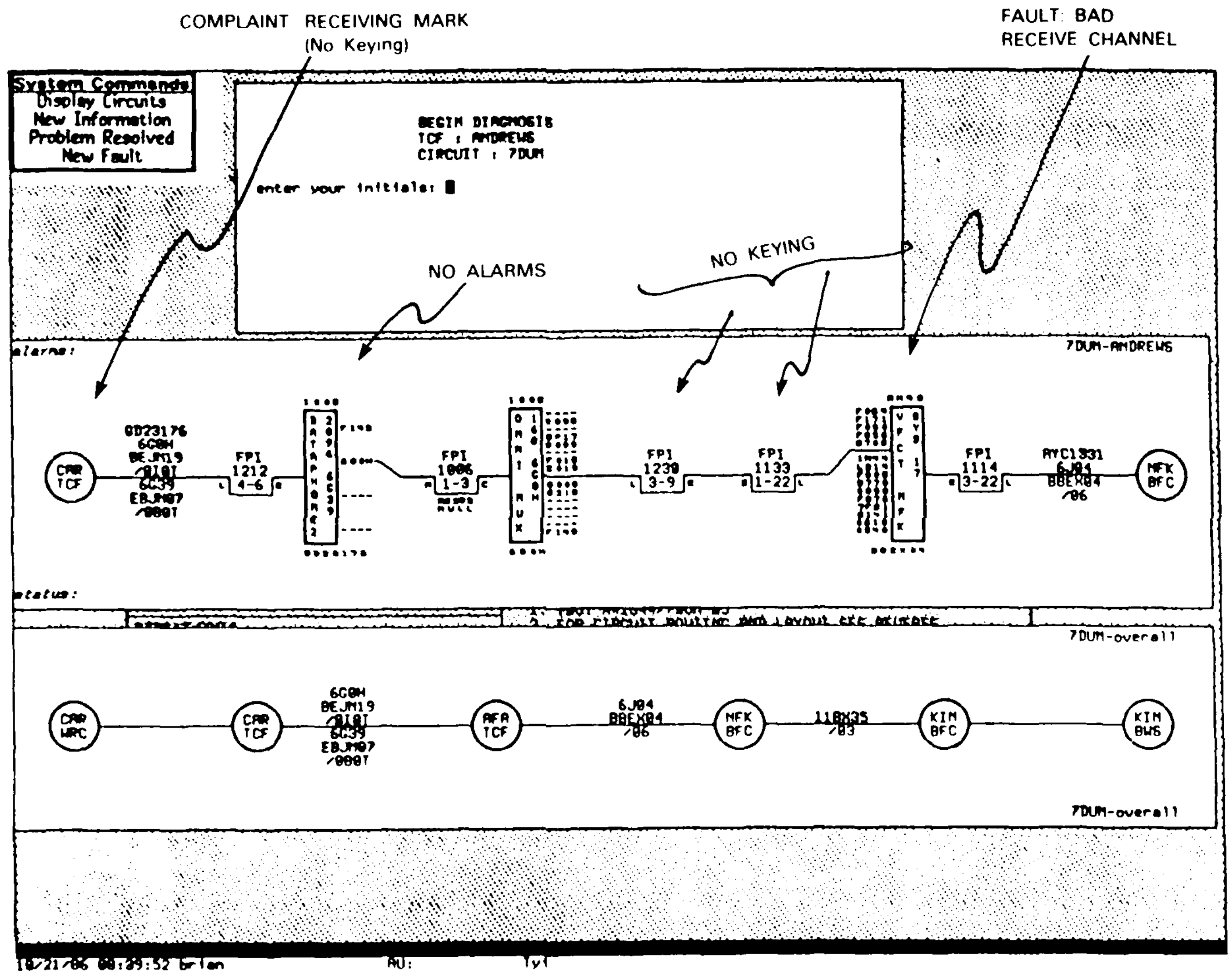

Figure 5(b). Symptoms of assumed fault.

Figures 6 and 7 show the system being informed as to the type of complaint (Receiving-Mark) and the source of the complaint (Carswell). Figure 8 shows the system displaying a mouse-sensitive image of the alarm panel of an ATT-2096. The darkened items are those that are "on" in the normal state, and in this case the user need only mouse EXIT to indicate that no alarms are active. Mouse-sensitive alarm panel images are used by the Expert System for all devices having alarms. Care has been taken to graphically recreate the exact appearance of the panel of each device; this is intended to make the system easier to learn and use.

2.1.4.2 Signal-Tracing Strategy

Having found no useful alarm information, the system initiates a signal-tracing strategy to isolate the faulty component. Since the problem exists in the signal being sent from NFK-BFC to CAR-TCF, the first place to check whether a signal is present is at jack FPI-1133-1-22 (Fig. 9), the upstream-most digital jack that carries only 7DUM. Note the dashed box around the jack; this box indicates the current focus of attention of the system, and always identifies the device that the user would have to find in order to make observations or run tests currently needed in the diagnosis process. In this case the user is mousing the word NO in the window at the top center of the screen. Figure 9 also shows the status (RECEIVING-MARK) under the Carswell TCF. The status line is continually updated for all components of the circuit during the diagnosis.

Since there is no signal at jack FPI-1133-1-22, the system looks upstream and considers the VFCT. Figure 10 shows the system asking if there are any good signals coming from the VFCT. This will help determine

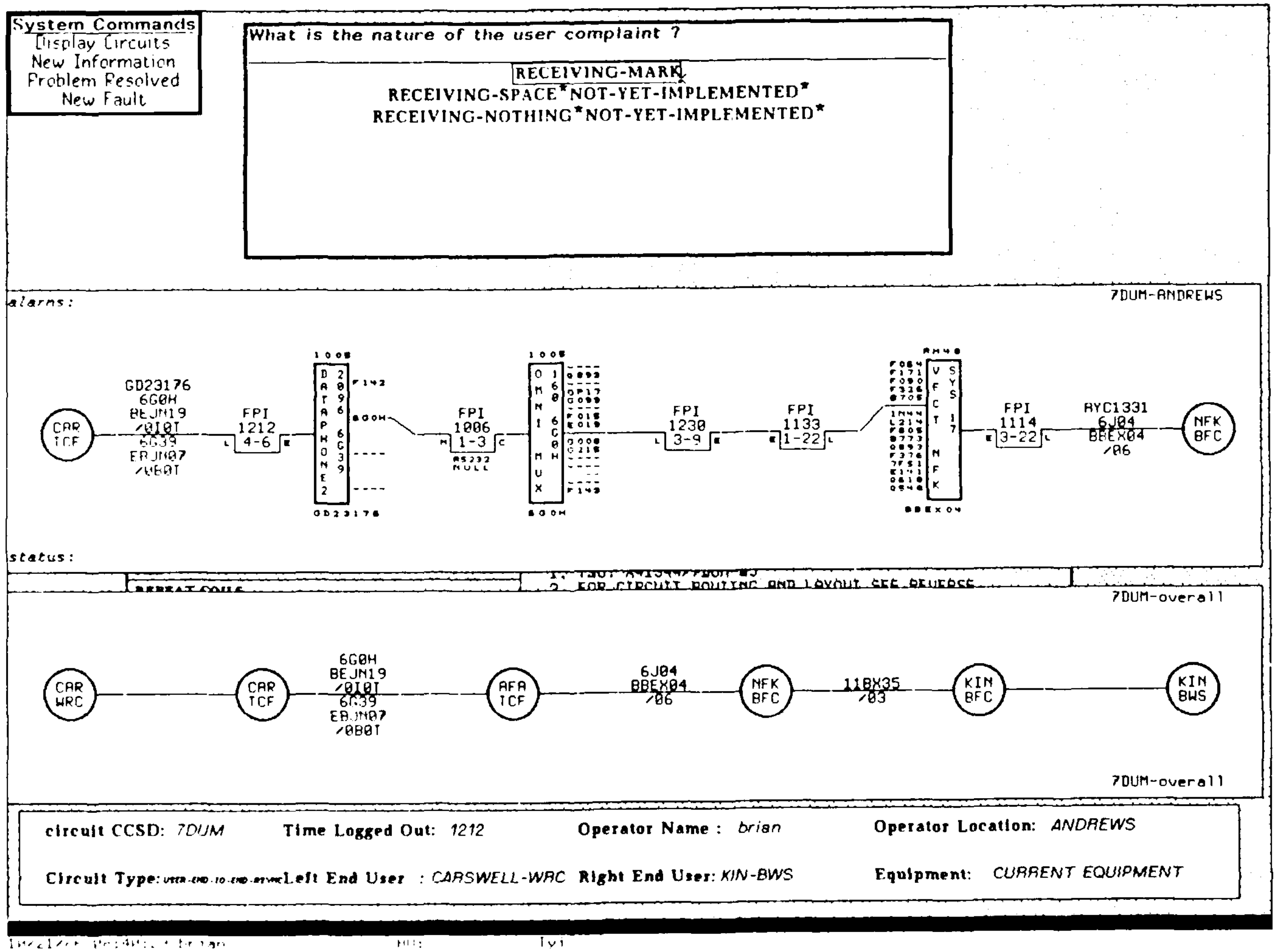

Figure 6. Complaint type menu.

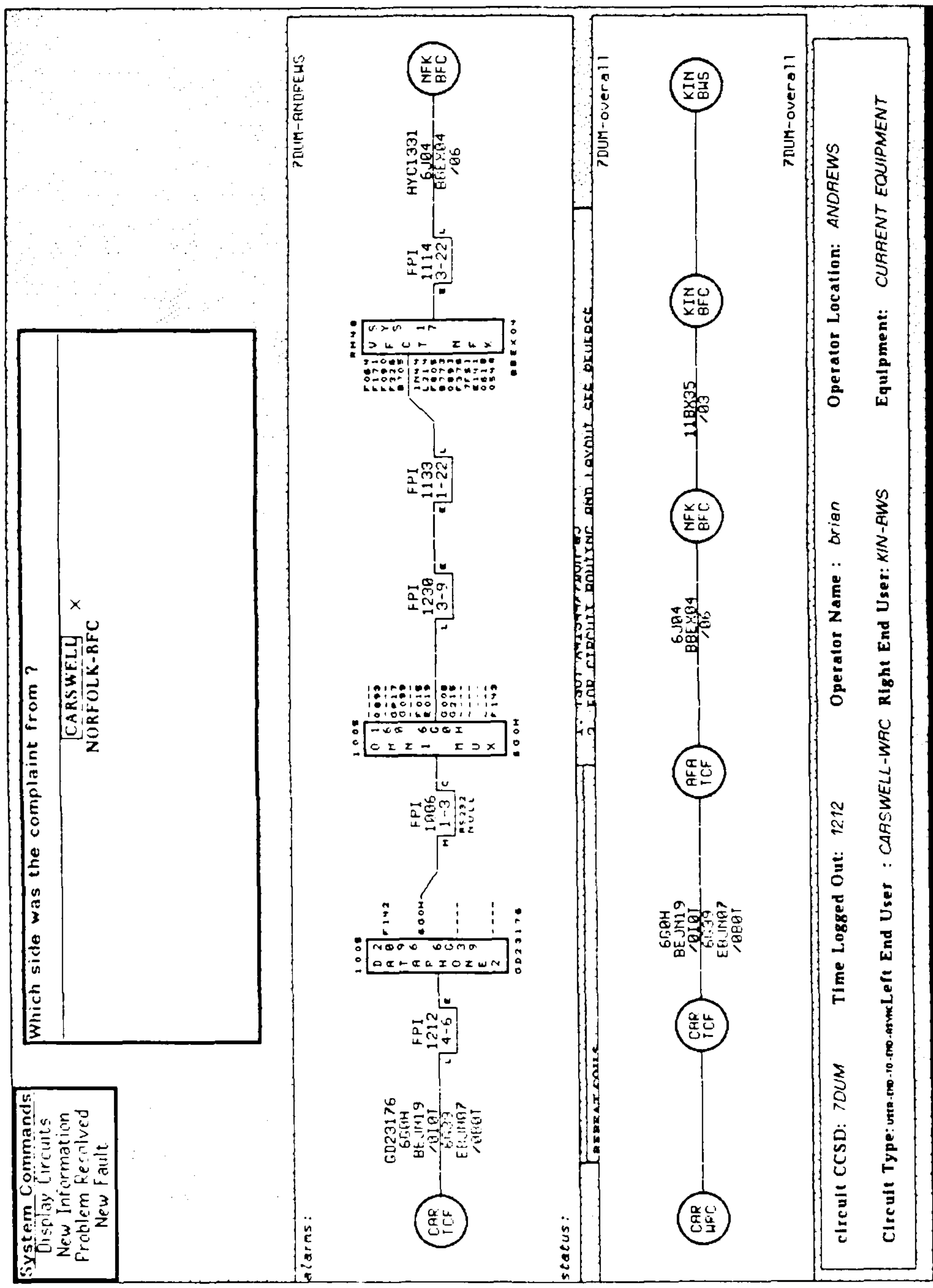

Figure 7. Complaint source menu.

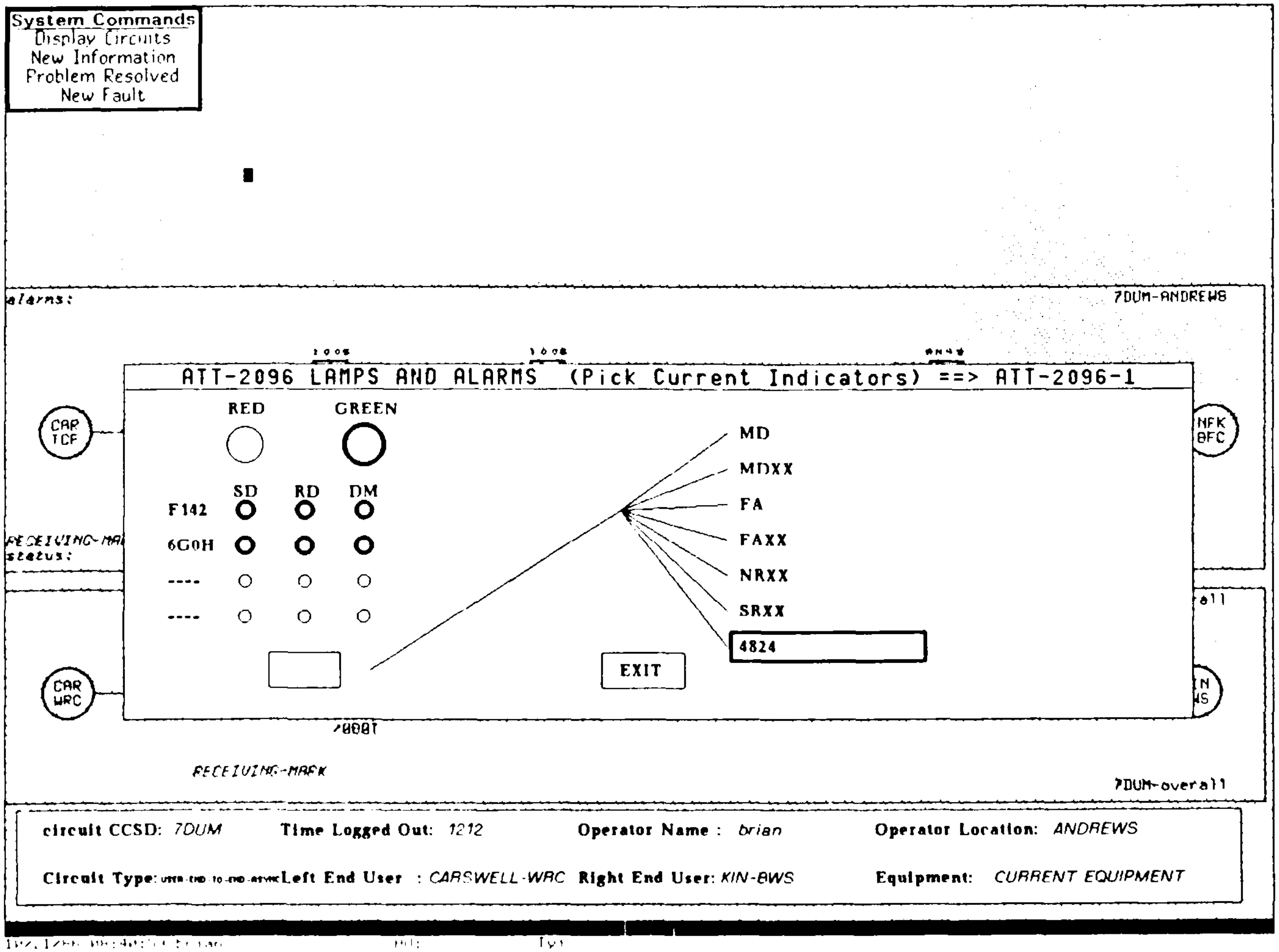

Figure 8. Alarm panel image.

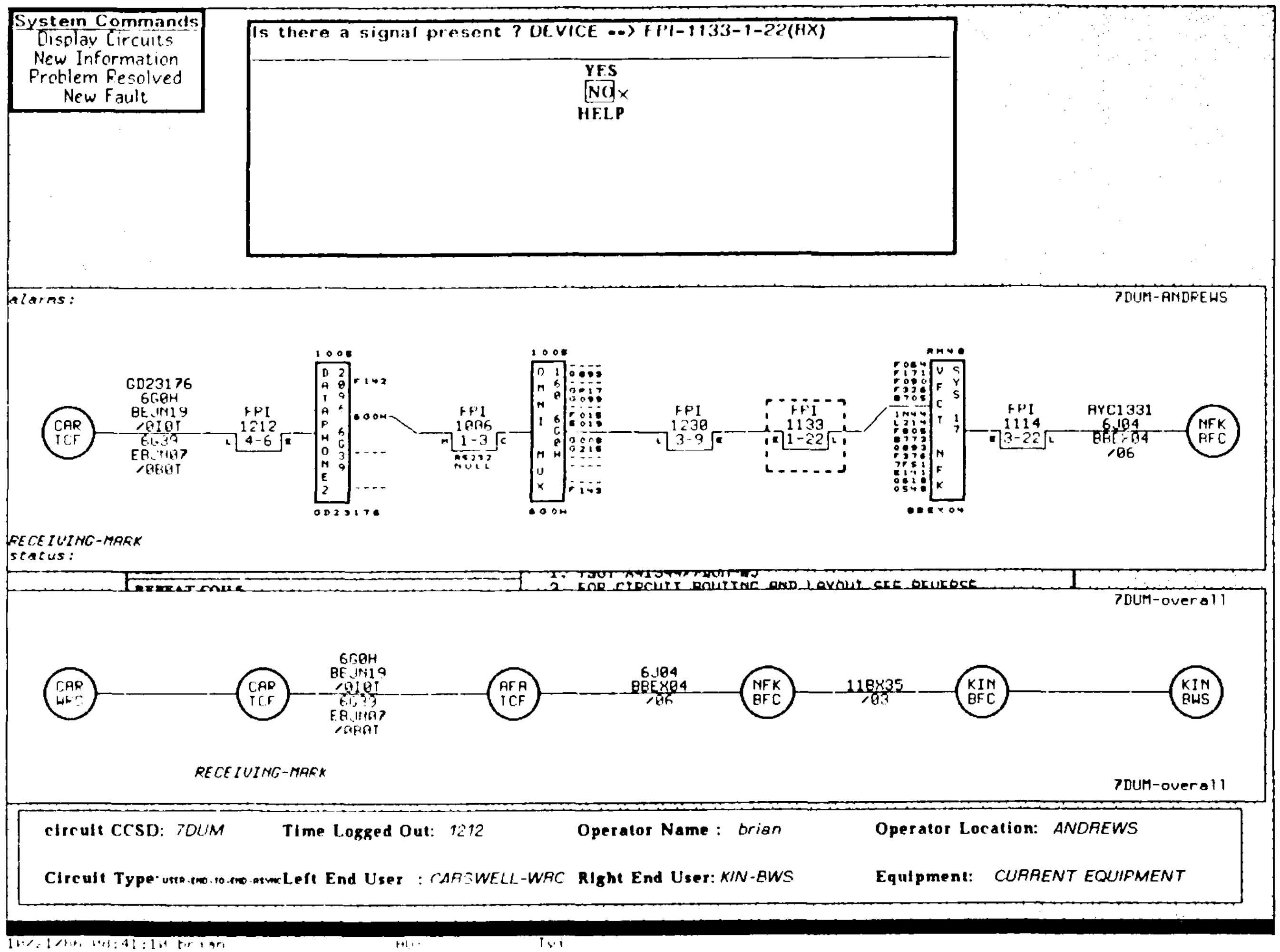

Figure 9. Signal tracing query.

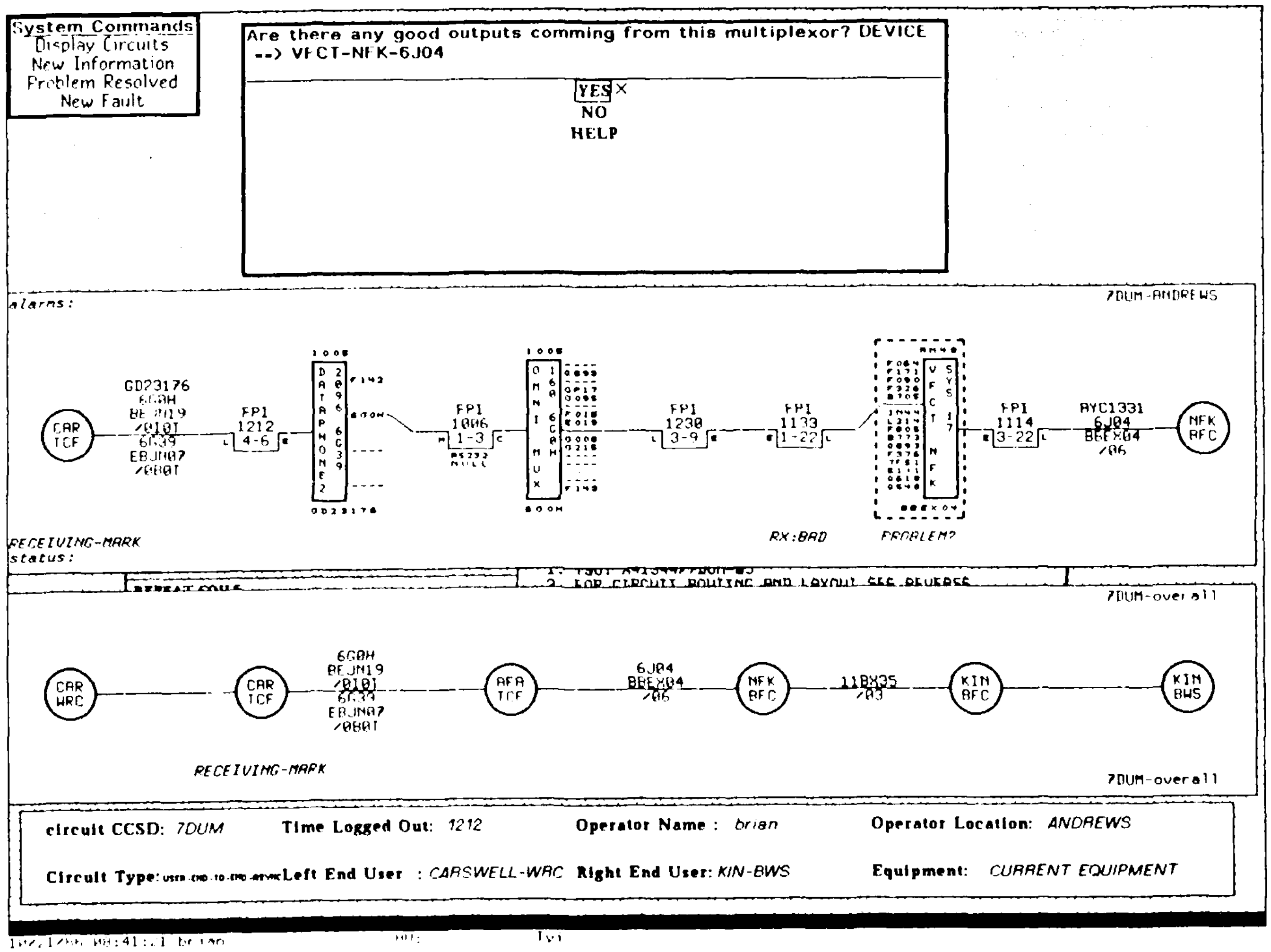

Figure 10. VFCT good/bad query.

whether there is a problem with the entire trunk, or just the channel carrying 7DUM on the trunk. Since the user is mousing the reply YES the system must find out whether the upstream tech control facility, NFK-BFC, is sending a signal on 7DUM (Fig. 11). At this point the user would call up NFK-BFC and ask them to verify that they are sending the signal, and the user would mouse the reply YES as shown. The system therefore concludes that only the channel carrying 7DUM on the trunk is faulty. This could be caused by a bad VFCT component at either Andrews or Norfolk.

2.1.4.3 Circuit Restoration

The signal-tracing strategy has isolated the fault to channel 7DUM riding on trunk 6J04. At this point the system recognizes that service can be restored immediately on 7DUM by substitution of good equipment, leaving the actual identification of the failed board or component to be completed at leisure. The easiest restoration procedure would be to locate a spare channel on the VFCT on trunk 6J04 and (coordinating with a tech controller at Norfolk) switch 7DUM over to it. The system discovers, however, that there are no spare channels on 6J04; all the inputs on the left of the VFCT have circuit designators filled in. Fortunately the system knows that Andrews operates several VFCT trunks to Norfolk, and is able to find a spare channel on one of them, namely trunk 6H34. The patch is coordinated with NFK-BFC, and is shown graphically in Fig. 12. This display uses curved lines to indicate patch cords, clearly indicating the patches necessary to implement the switch of 7DUM from the faulty channel on 6J04 to a new channel on 6H34.

After the restoration is completed the system produces the DD Form 1443 TROUBLE AND RESTORATION RECORD (Fig. 13) that is normally filled out

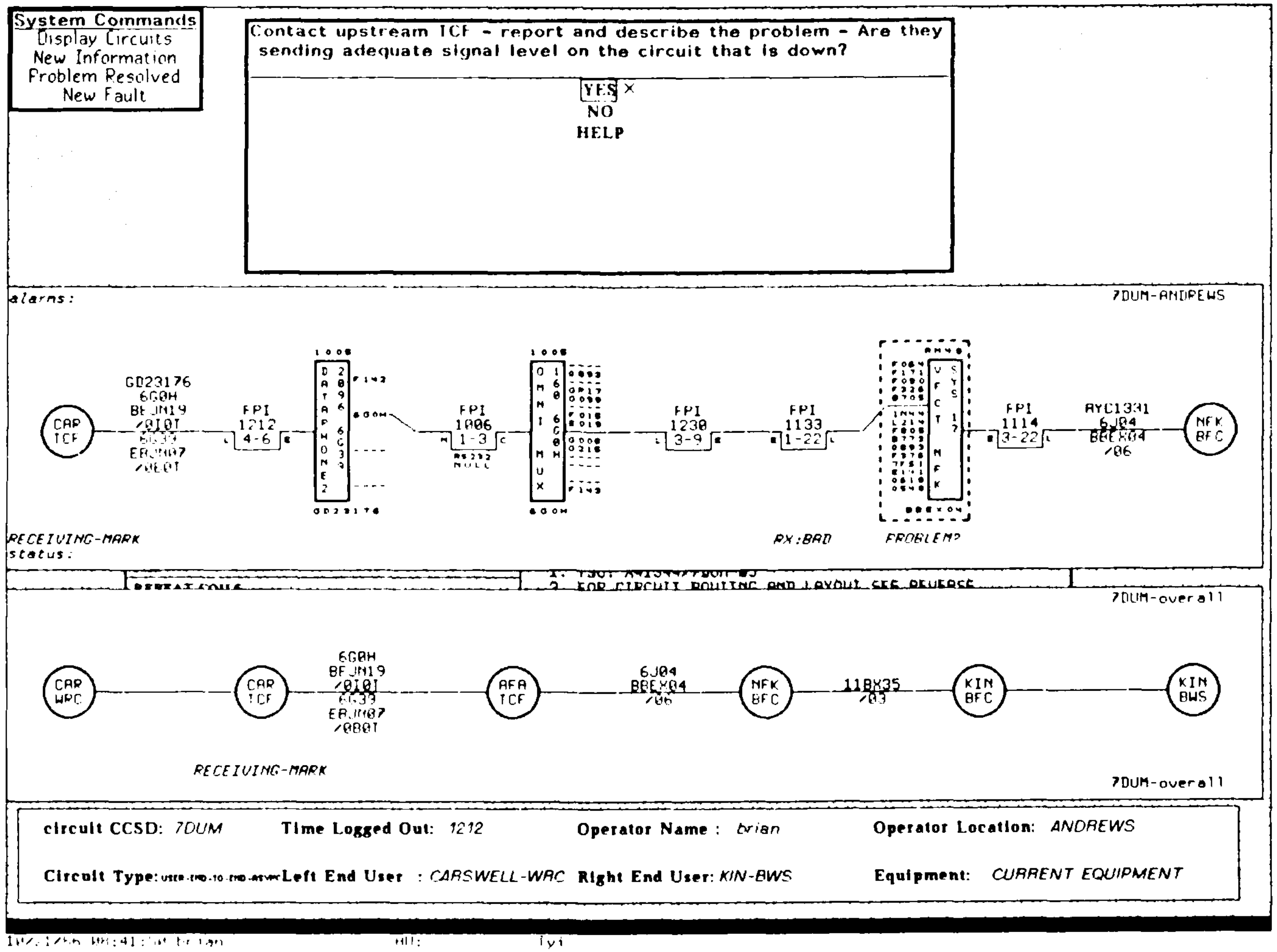

Figure 11. Interaction with upstream TCF.

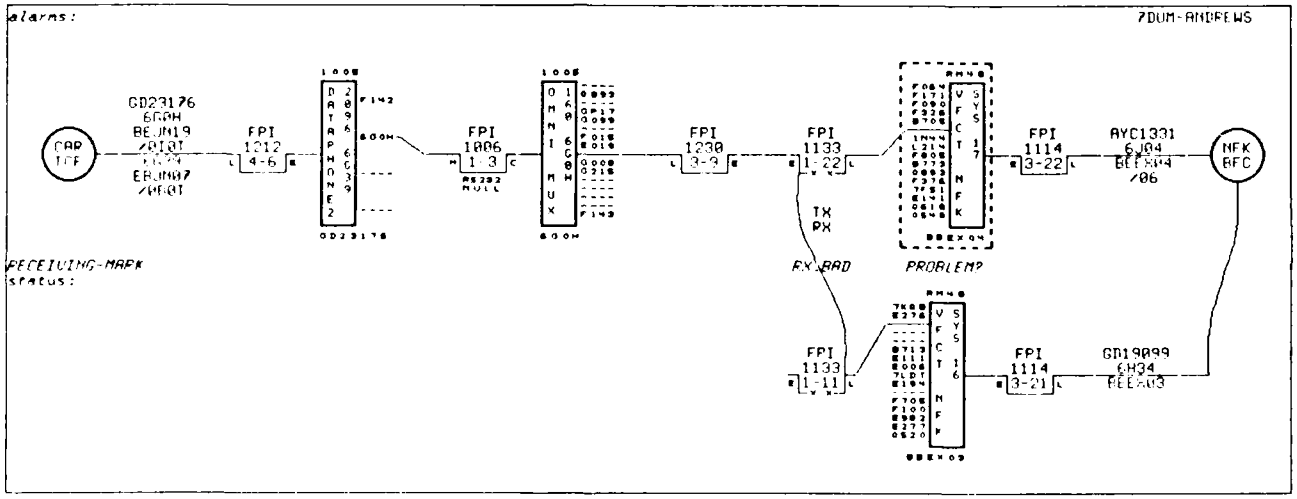

Figure 12. Recommended patch to restore service.

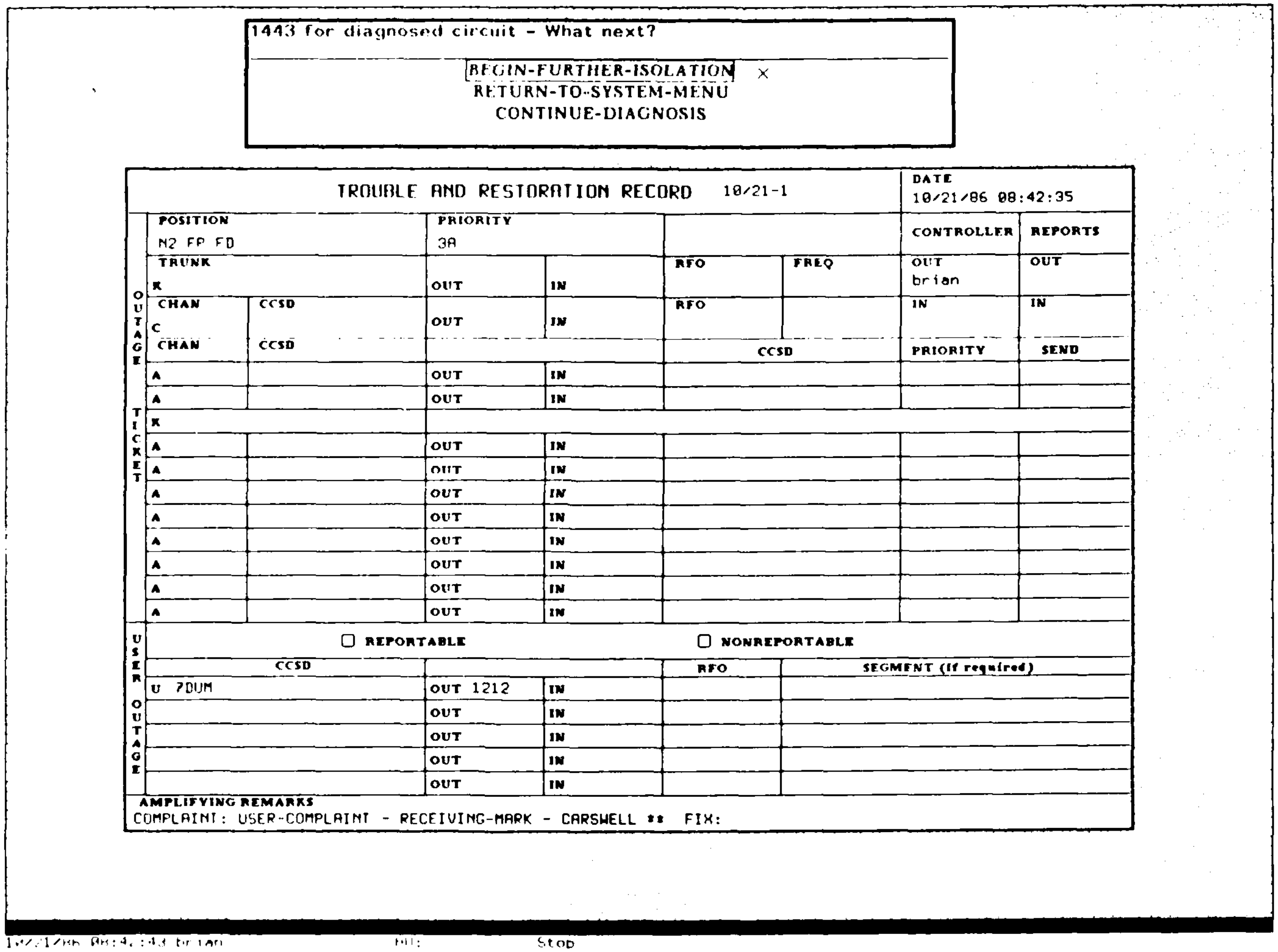

Figure 13. 1443 display.

by the tech controller after each outage. This one is shown only partially filled out. Work is currently in progress to allow the system to complete the form.

2.1.4.4 Post-Restoration Fault Isolation

Although at this point service has been restored on 7DUM, the system has not yet identified the component that must be repaired. At his first opportunity, a tech controller working on this problem would perform a finer-grained fault isolation so that the appropriate repair service personnel can be dispatched. For example, the symptoms in the scenario described above could have been caused by a fault in either the VFCT at Andrews or the VFCT at the other end of the trunk at Norfolk. One menu item above the 1443 card (Fig. 13), BEGIN-FURTHER-ISOLATION, initiates this process. It is not illustrated in the present scenario because this section of the system is currently under development.

2.1.5 Fault Diagnosis and Circuit Restoration Summary

The goal of this section has been to familiarize the reader with the complexity and the issues involved in performing fault diagnosis and circuit restoration on a network of this magnitude. Discussion of the problem dimensions, programming environment, and system architecture were intended to illustrate the nature of the problem and how it is being attacked. The level of expertise now incorporated was described in terms of the current extent of three system characteristics: devices implemented, fault isolation strategies implemented, and the methods of circuit restoration now available. A detailed demonstration scenario was presented to give the reader both a general feel for the problem solving process, and

an introduction to the user interface and graphics capabilities of the system.

2.2 Data Entry and Management

One of the prerequisites for running ETC is the existence of a database of circuits and devices. The correct and efficient creation of such a database is a significant project in its own right.

The database contains information from a variety of sources. The front of the DD Form 1441 "Circuit Data" card in current use contains basic information that must be placed in ETC's database for each circuit. The back of the 1441 card typically has a hand-drawn graphic layout of the circuit that may provide additional useful information for the database. Finally, on-site observations and various other sources may provide supplementary data that needs to be incorporated in the database. For our purposes here we will assume that the information has been located; it remains for us to enter it into the database.

In the early days of the ETC project it was expedient to build the database manually by invoking the Symbolics system editor and manipulating the various files that contain circuit layout and device information. Such a procedure is cumbersome and error-prone, and does not provide any validity-checking of the information that is entered. Operation of the editor is complex enough that it is not feasible for military operations personnel. Furthermore, the inter-relationships of the various pieces of information, e.g., the circuit layout and the devices involved, must be determined entirely by the person entering the information. Clearly, a system is needed for convenient and error-free management of the database.

Such a software system could serve many purposes. It could satisfy our short-term needs to enter additional circuits in our database. In the field it could enable one to transfer the contents of a site's 1441 card file and related information into the database and thereby be able to test ETC under realistic conditions. On a long-term basis it could enable one to generate and maintain a site's file of 1441 cards and related information completely in the computer.

These motivations led us to begin work on CADET (acronym for Circuit And Device Entry Tool). We began working on CADET toward the end of FY86 when it became obvious to us (and to personnel from Scott AFB who were attending a demo of ETC) that the manual editing approach was inadequate. We have produced a first version of CADET which handles the entry of a 1441 card and the circuit involved, provided that the underlying trunk circuit and devices have previously been entered. Further work is being pursued to extend the scope of CADET.

2.2.1 Design Goals

Our design goals for CADET include the following:

1. Familiar representation: Since the 1441 card is the medium used by the Tech Controller for information about a circuit, and since we wanted to provide a means for entering such cards into the database, we felt that the representation that CADET's user sees on the terminal display should be a replica of a 1441 card. This replica could be the framework in which information is solicited from the user.

2. Interactive: CADET should be interactive, providing immediate feedback to the user. Such feedback could be a request for more information about a datum that was just entered, an error complaint about

it, or a request for the next datum. These responses should occur while the user's actions are still fresh in his mind.

3. Smart typewriter: CADET can be a smart typewriter by providing automatic positioning to each field of the 1441 card in turn, forcing the user to provide the contents of a field that must be filled in before going on to the next field, preventing the overlapping of fields, complaining about errors in fields, etc.

4. Minimize typing: As a smart typewriter, CADET should supply, wherever possible, a "pre-typed" menu of permissible responses to a request. Such a menu provides at a glance the set of permissible choices, thereby clarifying for the user exactly what is expected. Furthermore, choosing from a menu avoids any possibility of typing errors.

5. Computer experience not needed: CADET should provide facilities directly related to the function of generating and modifying 1441 cards without demanding that the user have experience in programming and using computers. In particular, the user should not be required to learn computer editors, languages, and translators and should be shielded from the operating system as much as possible.

6. Error and validity checking: CADET should check the data provided by the user for correctness, validity, and consistency with other data in the database as well as with other data that has just been entered. If an error is detected, the user should be required to correct it on the spot.

7. Easy modification: Besides entering new information, the user should be able to conveniently modify or remove previously entered information.

8. Detailed operating instructions: At all times the user should be informed of what is expected and the various actions that he can perform.

2.2.2 Current Status

We have produced an early version of CADET which, for the most part, satisfies the goals described above. Subject to its limitations, CADET is usable in a variety of situations.

CADET is one of the activities that can be selected from the main menu of ETC. As its first action upon being selected, CADET asks the user for the name of the circuit to be entered or modified. If the user responds with the name of a circuit that already exists in the database, CADET produces a display of the 1441 card for that circuit and affords the user the opportunity to correct any entry on the card. If the circuit does not already exist, then a blank card is displayed and CADET begins enforcing a discipline upon the user of entering data for each field on the card in turn before going on to the next field. At any time in the data entry process, however, the user is free to interrupt work on the current field to go back and make a change or correction in a field already filled in. Each field of the card has entry and error-checking routines associated with it in a table-driven fashion. These routines may include menus, rules for valid data, and other characteristics of the field in question. Additionally, each field has an indication as to whether it must be filled in or may be left blank. In the former case, CADET does not allow the user to leave the field blank and go on to another field.

Heavy use is made of the Symbolics graphics and interactive capabilities. In order to focus the user's attention, the field currently being accessed is highlighted in reverse video. Each field is a mouse-sensitive region, so that the mouse can be used to select a field

when out-of-order modifications are desired. As one moves the mouse, each field passed over is highlighted by means of a thick line around it, thereby informing the user as to which field would become the current one were he to click the left mouse button. When all available space in a field has been filled by typing, any attempt to type more into it results in a flash of the screen and the sounding of a beep.

A window is used by CADET to provide instructions to the user. The contents of this window depend upon the field being accessed and whether it is empty or filled. The instructions tell the user how to fill an empty field, how to empty a filled field (if it may be emptied), and how to modify a field. A specific message tells the user if the field is one that must be filled. The aim of the instructions window is to leave no doubts in the novice user's mind as to what he may do. On the other hand, a knowledgeable user can proceed rapidly with the data entry process by simply not reading the instructions.

At any time a user may cancel the entire session and return to the main menu. When the user has passed through the last field of the card (or when he is editing an existing card) he is the given the option of accepting the card and thereby incorporating it into the database. If he does accept the card, then a new database entry is made (in the case of a new circuit) or a previously-existing entry is modified to reflect the desired changes.

Demonstrations of the current version of CADET have been very positively received. Some viewers have even felt that it would be a useful tool as is, without any further extensions.

2.2.3 An Example

Figure 14 shows a dump of the Symbolics terminal screen during a session of CADET. We now describe the contents of the screen.

The big window in the center of the display is a replica of the front of a 1441 card that has been filled in for circuit "7DUM" (see "CCSD" fields in the second and bottom rows). In the top row on the right there are two mouse-sensitive regions: "CANCEL?" for cancelling the entire session, and "ACCEPT?" for accepting the session and incorporating the material into the database. (For protection, mousing either of these two regions results in a request for confirmation from the user before the action is carried out.)

Each field in the card-window is mouse-sensitive and may be selected as desired for modifications. In particular, "TYPE CIRCUIT" is the currently-selected field and is indicated as such by being displayed in reverse video. By looking at the Instructions window (the topmost one) we can see that this current field was selected for modification.

The Instructions window tells us that the current field may not be left blank (unlike some other fields on the card, which have been left blank). It tells us the old contents that are being changed and how we may reinstate them without changing them. Finally it tells us that CADET is waiting for the user to choose a new item from the menu that is displayed immediately to the left of the card-window.

A careful examination of the situation allows us to infer what has happened. The user originally inserted into the TYPE CIRCUIT field the contents "FP FD NS". He has since realized that this was an error and that

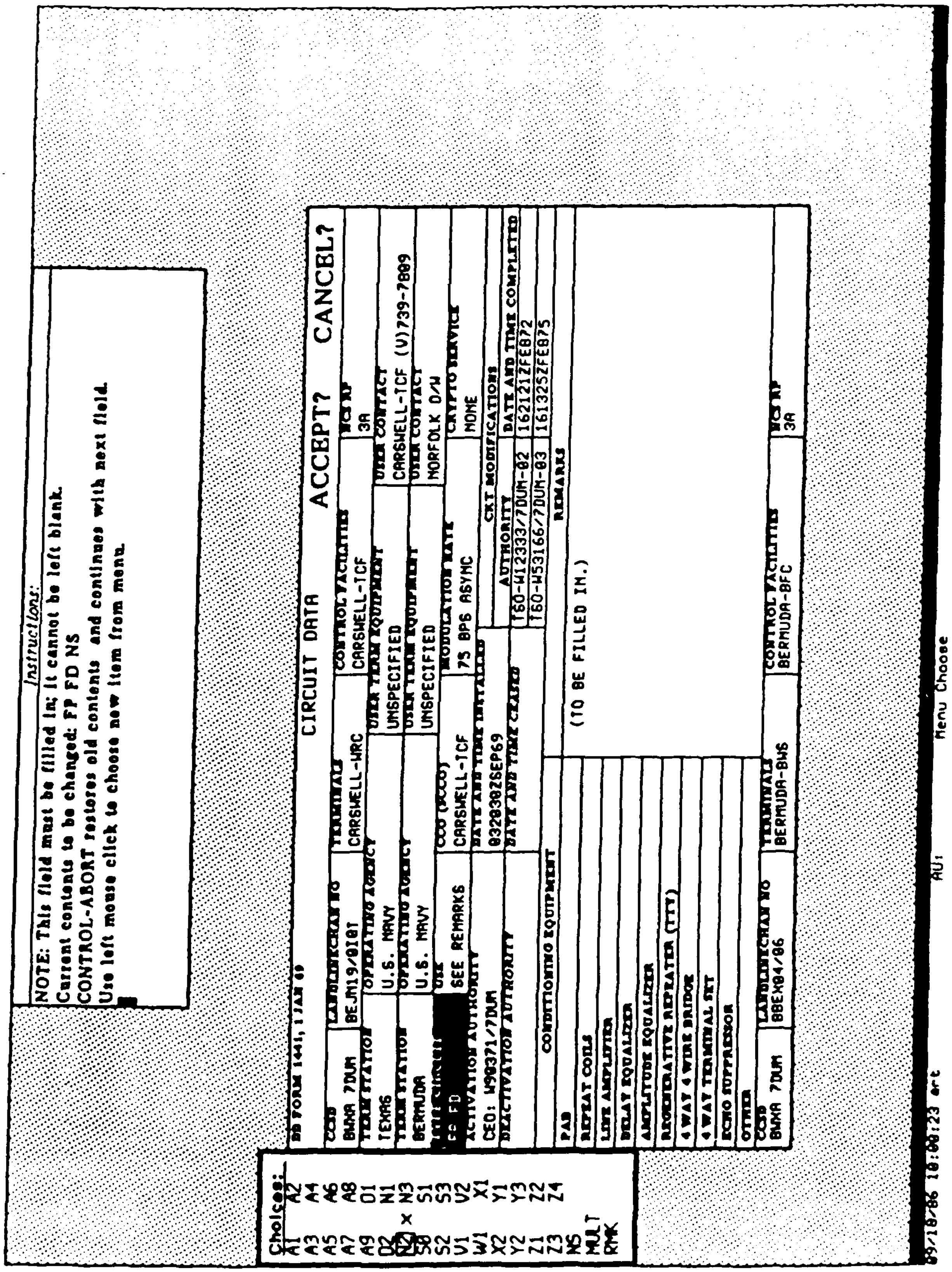

Figure 14. CADET display.

"NS" should be "N2". He therefore moused the field, reinserted "FP FD", and is mousing on the "N2" in the menu (note the box around "N2" in the menu) in anticipation of inserting it into the field. Once he has completed this field, he may go on to another field for modification, or he may accept the card, or he may even cancel the whole session.

2.2.4 Future Work

Much work needs to be done before CADET can reasonably be regarded as a prototype of a field-deployable system. We expect to deal with many of these issues before the field demonstration scheduled for February 1987 at Andrews AFB.

The error and validity checking for some of the fields is fairly extensive, but for the others it is minimal or non-existent. We need to fill these gaps. For example, some fields may be filled only from a predefined set of entries; while this is easily handled with mouse-sensitive menus for fields having small sets of permissible entries, other fields may have hundreds of allowed choices. We must decide how best to handle such big sets, from the points of view of checking and presenting to the user the permissible responses.

The current implementation of CADET assumes that the database already contains descriptions of all trunks that will carry any new user circuit being entered. We plan to extend CADET to handle the input of new trunks. One possibility involves a push-down mechanism, allowing the user to enter a trunk in the middle of the process of entering a user circuit.

Another limitation of CADET is the assumption that the database already contains descriptions of all the devices involved in the circuit

being entered. We are planning to provide a mechanism for entering new devices and their specifications into the database. Finally, we need mechanisms for making permanent modifications to the database, i.e., onto the disk, rather than the current limitation of merely updating the database in active memory.

3. LESSONS LEARNED

The Expert Tech Controller project has encountered many obstacles that are typical of expert system development. The solutions developed for these specific problems may contribute to a more global domain-independent understanding of viable techniques for expert system design and implementation.

3.1. Software Environment

Probably the most publicized controversy in expert system development is the debate about what kinds of hardware and software development environments are necessary or desirable. This section will discuss the decisions made thus far in this project, and how these decisions have impacted the work.

Software environments for most Artificial Intelligence applications in the US have traditionally been based in LISP. LISP by itself is a high-level language that facilitates symbolic processing. Development of the Expert Tech Controller has been done exclusively with LISP and LISP-based tools. These tools include the Symbolics system software features and ART, the expert system shell developed by Inference Corporation.

The advantages of the Symbolics software environment include rapid prototyping features; incremental LISP compilation; a "smart" LISP editor;

an object oriented programming facility (Flavors); and extensive graphics capabilities. The main disadvantage of this programming environment is that it is machine-dependent, with the machine being very expensive. Our opinion of the situation seems to coincide with the general consensus in the expert system development world. For prototyping and development the environment is extremely valuable. For delivery systems, however, the costs of Symbolics hardware, software, and maintenance contracts are so high that one would like to port any final software product to a more conventional, less expensive environment. The problem with this is that many features do not port gracefully. Consideration of portability during development, by avoiding such features, may inhibit the development process.

The major software tool used for the development of the Expert Tech Controller has been ART. We found the ART environment to be quite useful during early stages of system development. The inference mechanism of ART, like those of other typical shells, seems to be quite effective for small to moderate-sized systems. As a system grows, a pure rule-based system tends to push the capability of these inference mechanisms. The solution devised for the Expert Tech Controller has been to encode directly in LISP those portions of the system that are procedural rather than rule-based in nature; this includes (for example) many of the individual fault isolation strategies. When invoked as appropriate from within the rule-based structure that remains within ART, these sections execute very rapidly without causing the inferencing process to bog down. We have concluded that this approach allows convenient access to the best features of both

software worlds, namely the power of rule-based processing and the efficiency of LISP code. The problem with this approach is determining which subproblems should in fact be rule-based. While this identification process may take considerable experimentation, nevertheless we are convinced that our use of both software options has greatly enhanced system development.

3.2. Hardware Environment

Although the cost of specialized LISP processing hardware is high, the investment is worthwhile for system prototyping and development because the fast execution of LISP greatly enhances programmer productivity. As noted above, however, high costs may exclude specialized LISP machines from consideration as delivery vehicles. A possible solution is becoming available in the form of conventional computer work stations, whose manufacturers are beginning to attain enough processing power to run LISP at an acceptable speed for delivery purposes. Also, Inference Corporation has recently begun offering the capability of transforming LISP-based ART systems into the C language for delivery on one of the numerous machines that support C; while this has the advantage of avoiding ART-related problems, it does not resolve the probable incompatibility of graphics and I/O systems.

3.3. Database Considerations

The combination of specialized symbolic processing hardware, the ART shell and a large amount of data presents a complex database problem. Initially we implemented the database in Schemata, the frame-based knowledge representation mechanism provided by ART. As the system expanded

it became obvious that the Schemata system involved unacceptable overhead and would be unable to handle the Expert Tech Controller database as it grew toward the required size. At this point we made a decision to retain the frame-based structure and increase efficiency by converting the database to Flavors, the Symbolics object-oriented programming facility. This improved matters, although it introduced a new problem in that the inferencing mechanism ART cannot directly access information in the Flavors-based database. Our solution to this problem has been to select the database information that is relevant to a problem-solving session and convert it from Flavors to Schemata in advance.

Recently we have begun addressing the issues affecting the realization of a more permanent database. The only reasonable way to deal with the quantity of data needed for problem domains like the Expert Tech Controller is to store it on disk. This issue will require considerable work, and will be discussed in the future.

3.4. Knowledge Engineering

We have found that there are a number of keys to effective knowledge engineering. First, there is no substitute for a bona fide expert with extensive experience in actually solving in actually solving the problems in question. We initially used manufacturers' manuals for some equipment items as supplementary sources of information that could be accessed at home, at our leisure; however, it turned out that the more formal diagnostic procedures in the manuals were unnecessarily detailed and inefficient, compared with the shortcuts and rules of thumb typically used by the human experts.

It is also desirable to have more than one expert. This has the advantage of preventing the system from becoming distorted by one person's idiosyncrasies, and the disadvantage of forcing the knowledge engineer to deal with conflicting expert opinions. A major goal of the knowledge engineer must be to merge these diverse opinions in a way that keads to the most consistent and effective procedures.

We have found that one good way to motivate the domain experts is to quickly and accurately implement their suggested changes before the next knowledge engineering session. Perceived problems in the system's reasoning will not bother the experts so much, once they realizes how quickly they can get changes made.

Although distance has limited the frequency of our interactions with the domain experts, our experience indicates that shorter, more frequent knowledge engineering sessions may be more effective than longer, less frequent ones. This provides for quick feedback on a smaller number of changes, and leads to more efficient use of the expert's time.

3.5. The User Interface

When dealing with end users and domain experts having little or no computer experience, the user interface is a critical consideration. There is high potential for a communication bottleneck. The issue is complicated in many cases, as in the Expert Tech Controller, when detailed graphics are essential for accurately communicating about the problem domain. We have found that the overused term "user friendly", and effective transfer of information content, should represent the major goals of the user interface. High resolution bit-mapped graphics and extensive use of the mouse can aid in achieving both of these goals.

Another user interface issue we are addressing is that of minimizing the demands upon the operator. In the Expert Tech Controller domain, many requested inputs are simply readings of meters, device alarm panels, and other indicators. The process of making these observations and inputting the results can be time-consuming and dull to the user. Automating some or all of these inputs can make more efficient use of time for both the expert system and the user.

3.6. Knowledge Representation

The choice of knowledge representation is probably the most critical issue in expert system design and implementation. It is also the major bottleneck in enabling inexperienced knowledge engineers, or domain experts themselves, to build expert systems. Although the frame-based mechanisms offered by state-of-the-art expert system shells are very powerful, most domains will still require considerable customization to accurately portray domain information.

The knowledge representation technique used in the Expert Tech Controller could best be characterized as a modified frame-based structure. The man-hours expended in the modification process, however, must not be underestimated. It is a slow process, and it appears to take place throughout system development. It should be noted that Symbolics LISP provides an excellent environment for making these modifications.

3.7. Data Acquisition

Data acquisition can be a major hurdle when trying to get an expert system from the prototype stage to the delivery stage. In the Expert Tech Controller, the feasibility of fault diagnosis can currently be

demonstrated on a few tens of circuits. To be useful in the field, however, ETC must contain data on several hundred circuits.

At present we are building a data acquisition system that will allow the tech controllers to conveniently enter data for large numbers of additional circuits. This will greatly decrease the amount of time currently spent on this process by the knowledge engineers. It will also provide a mechanism for circuit addition and modification after the expert system is fielded. The creation of this data acquisition mechanism is a challenging problem because it must be simple to use, yet has to convert the information obtained into the complex data structures expected by fault diagnosis and other modules.

3.8. Knowledge Acquisition

Currently, the only method for adding knowledge to the Expert Tech Controller is for the knowledge engineer to add LISP code or ART rules. Automation of the knowledge acquisition process is a topic being addressed by many researchers. To the extent that we do address this topic in the future, our emphasis is likely to be placed on: modularizing the system to enhance automatic production of modules; creation of a method to go from the specifications for a new device to diagnostic rules and procedures for the device; use of inherited diagnostics for device "types"; and development of modules that automatically build the procedures to enhance graphics, in terms of both circuit displays and alarm panel displays.

4. TESTBED ARCHITECTURE STUDY

It appears that Machine Intelligence techniques offer possibilities for significant improvements at many levels of System Control in the

Defense Communications System (DCS). The Expert Tech Controller project described above, which addresses the foundation layer of System Control, was chosen for the initial implementation because it involves a set of clearly-definable problems and existing centers of expertise for solving them, and promises to yield interesting results in the near term. As a complement to this project, we have undertaken a study in FY86 of the applications of Machine Intelligence techniques at other levels of the System Control structure. This section of the report describes the results of the study, specifically including recommendations for a simulation-based testbed architecture for evaluating Sytem Control techniques. The study results are presented in the broader sense as issues of importance for the Government to consider in planning future programs, rather than specific proposals for new work.

We first examine the projected direction of advances in DCS communications technology and organization, and then identify problem areas in which machine intelligence would be of benefit. This provides a basis for determining, in a general way, the expected functionality of future control systems which incorporate machine intelligence. Following from this description is an outline of the form these systems might take, and a discussion of the research problems which must be addressed in order to build these systems. At the conclusion we have recommendations for near-term research objectives, work to follow after these objectives have been met, and some long-term goals.

4.1 The Future DCS

The DCS is currently evolving in terms of both communications technology and organizational structure. As more and more digital communications equipment has been introduced into the network, the possibilities for automated data collection and control have increased greatly. The complexity of system control problems has also grown as a result of these changes. Although digital equipment generally offers the advantage of robust operation, requiring little day-to-day maintenance, the additional functionality provided often means that human operators must have a sophisticated level of knowledge to understand the optimum ways to test, diagnose, and reconfigure the equipment. The increased reliability of digital equipment has also reduced the opportunities for human operators to gain real-time practical experience in network control.

The organization of the DCS control structure is also changing with the introduction of the concept of subregion control facilities. This change will place a greater emphasis on distributed control of the circuit switched network, and integration of monitoring and control across the various DCS subsystem boundaries. In the past, control of the transmission system and each of the various networks which utilize the system has operated in a rather independent manner. As the future DCS evolves, a system controller will be expected to integrate status data across subsystems and networks, and make decisions regarding allocation of resources which may have wide-ranging implications. It will become necessary for a controller to know the answers to "What if ... ?" questions for a much wider range of situations than is currently expected.

In summary, the DCS is becoming more reliable and more automated in a way which increases the automation of data collection and control execution, but may place a greater burden on system control. Effective control requires carefully considered decision making — a task which is becoming more difficult as a result of increased complexity. At the same time, system control operators are developing less experience with problems, especially those of the magnitude and scope which might arise in a real crisis. It is in this area of providing automated assistance for decision making, particularly in stress conditions, that the application of machine intelligence techniques has the greatest potential benefit for system control.

4.2 Problem Areas for Machine Intelligence Applications

There is a wide range of problem areas which might be addressed in an effort to provide automated assistance for decision making. Within the DCS control structure at the upper levels (e.g., ACOC or DCAOC), decision making requires reasoning about what data is important and must be considered, and what data is not directly relevant to the problem at hand. Further, a controller must be able to determine quickly what, if any, additional data is needed and how to find it. Thus, rather than present an operator with an enormous collection of facts gathered from several networks and subsystems around the world, it would be much more effective to interpret this data, using knowledge about these networks, and the role of this operator in controlling them. Once a particular crisis situation has been recognized, the controller often has to select from a large set of alternatives in responding to the crisis. An intelligent aide would assist

in this task by generating appropriate plans and recommending the best choices. Such a system would embody aspects of sensor data fusion, situation assessment, intelligent data base query, interactive task recognition, and planning.

There are several steps with which this problem might be approached. Initially, one or more independent automated decision aids might be developed. These would represent low-risk, well defined tasks. When completed, each aid would be a useful product, albeit in prototype form. More significantly, the work involved in designing, implementing, testing and evaluating each aid would be beneficial in building a base of knowledge and experience with the details of the problem domain. As this technology matures, the more difficult research problems should be addressed. We may envision an evolution of these independent aids toward an integrated system of cooperative, autonomous agents. The role of these problem-solving systems would shift from being an automated tool for the human controller to becoming a member of the system management and control team. Although such systems are clearly beyond today's technology, they serve as useful goals in understanding the direction for current research.

We now focus on a specific problem, namely network control for the Defense Switched Network (DSN). This network is of interest because it represents the introduction of a new system control problem. Unlike existing networks with which there is a large base of experience in network management, the DSN control must be developed from the ground up. Although there are many man-years of experience with circuit-switched voice networks, such as AUTOVON, the DSN differs significantly from a control

perspective. First, the DSN (as configured for the European theater) will utilize many more, but smaller, switches than AUTOVON. While this tends to increase control flexibility, it also means the network will behave differently. The choice of control action for any given situation in the DSN will not necessarily be the same as has been used for AUTOVON. Second, because of the larger number of switches, it is unlikely that a single, unaided controller will be able to maintain the level of cognizance over the entire network (just in Europe alone) necessary for optimum management. Third, as a result of the changes in DCS organizational structure mentioned earlier, the control of DSN will be distributed, in part, to the subregion control level, thus making control less centralized than it is with AUTOVON.

4.3 Architectures for Machine Intelligence Systems

At the core of typical machine intelligence systems are knowledge about the physical world of interest and a reasoning capability (the inference engine). The design issues are associated with acquiring, formalizing and representing this knowledge, and determining efficient control strategies for using the knowledge to reason about the problems to be solved. We illustrate an approach to this design process with an example based on the DSN control problem mentioned previously.

The key to designing an effective, knowledge-based DSN controller is a complete and detailed understanding of the knowledge needed to interpret the available data, to assess the current status of the network, and to recommend appropriate control actions. This knowledge takes a variety of forms, but may be divided into two broad categories: empirical and theoretical.

Empirical knowledge is derived from observations and experience. For example, past experience might tell us that during peak traffic periods the failure of one specific switch is likely to result in traffic overload at three others. Further, we may have observed that a particular control action, such as changing routing tables to distribute this load over a larger set of intermediate switches, would reduce the overload to manageable proportions.

Theoretical knowledge is based on the underlying physical and mathematical models we have developed for describing the behavior of real networks. We know from fundamental theory, for example, that the loss of all trunks connecting one part of the network to the rest will result in isolation of that part, and the failure of all call attempts between the isolated parts. This knowledge suggests a control action blocking all such call attempts at their source so as not to overload the network with attempts doomed to failure.

While these are admittedly oversimplified examples, they are intended only to illustrate some of the differences between empirical and theoretical knowledge. We observe that empirical knowledge often involves approximations and making judgments. Using empirical knowledge in these situations means that we must reason with inexact information or in the presence of uncertainty. For highly complex systems such as the DSN, it should be clear that although there may be great volumes of theoretical knowledge about each of the network components, our knowledge about the dynamics of network behavior must come largely from empirical evidence. The system is much too complex to be described by detailed mathematical

models. Thus for "expert-level performance", theory-based knowledge alone is not sufficient, but must be coupled with knowledge derived from experience and human insight.

Another perspective from which knowledge may be viewed is based on what the knowledge describes, rather than on how it was acquired. This is a significant distinguishing characteristic because it often influences the choice of knowledge representation. In the case of the DSN we need knowledge about the structure and form of the network; knowledge about the function of various network components; knowledge which describes expected network behavior under various traffic conditions; and knowledge of alternative control actions, including conditions under which actions should or should not be invoked. It is unlikely that a single form of knowledge representation would suffice for all of these categories.

Finding efficient control strategies for reasoning with this knowledge is the second major design issue. The number of alternative choices in solving network control problems is so large that simple exhaustive searching, especially under the demands of near real-time decision making, is not feasible. In addition, the issue of uncertain or inexact conclusions complicates even the simplest approaches. One approach is to use data from various sources to confirm hypotheses. This often provides a mechanism for effectively using inexact or uncertain data. The problem of large search spaces may be addressed by using human insight about network behavior to develop heuristics for guiding the search.

Each of these techniques adds complexity to the overall system. If not carefully managed, this complexity may easily overcome the designers'

ability to complete a successful operational system. A modular system may be built by using multiple, specialized problem solving agents which reason cooperatively to solve the problem. In the design of a machine intelligent controller for DSN we see a probable need for four such agents: an assessment agent, a planner, a routing strategist, and a controls strategist. The assessment function attempts to interpret data from DSN switches and other "external" data, such as transmission equipment status, so as to form conclusions about the current state of the network. The planner uses goals for desired network behavior and the conclusions from assessment to generate plans which guide the overall response of the control system to network problems. The routing strategist and the controls strategist represent specialized knowledge sources which incorporate both empirical and theoretical knowledge needed to answer questions such as "What is likely to happen if code blocking is introduced as a control action?", or "Which routing and preemption procedures are most likely to allow the greatest number of higher precedence calls to be completed under current network conditions?"

4.4 Research Issues

It should now be clear that there are a number of interesting research questions to be answered in developing architectures for future applications. For the specific problem of DSN control, we are forced to ask how we can acquire the necessary empirical knowledge. Not only do we not have a base of experience with DSN control, the network is not yet complete. To wait for a completed network and the time necessary for humans to become proficient seems unreasonable. An intelligent network

control aid would perhaps be most useful when human operators are least experienced. One approach is to develop the necessary insight and empirical knowledge in one or two highly skilled individuals be repeated use of simulations. These persons would then become the "experts" from whom the knowledge could be acquired. The next logical step is to investigate how closely these two processes may be linked; are there techniques for automating much of this learning and transfer of knowledge?

From a broader perspective, we are concerned with how new applications are tested and evaluated. This is an important area for systems which we want eventually to be placed in the hands of operators having weak training and essentially no understanding of how these systems work. We know from past experience that machine intelligence applications are often very fragile. As the problem size grows to realistic proportions, the complexity and scope of problem solving demands may exceed the capabilities in ways which lead to total failure. For systems in a real world environment, this is not acceptable. We need tools and facilities to conduct tests which push the problem solving demands to the limits of these systems. It is vital for continuing progress to know where and why systems fail. As more and more new applications are developed -- first as prototypes, then followed by optional field versions -- we need ways to evaluate system performance under realistic conditions without disrupting the real world.

4.5 Recommendations

For the near term we propose that the existing call-by-call simulator developed by Lincoln Laboratory be investigated for use as a tool in

developing the empirical knowledge needed for DSN control. A preliminary examination has indicated that some enhancements would be necessary; for example, additional network control actions are required. This is a fairly short-term, low-risk investment, since the bulk of the simulator development has already been done.

Objectives for follow-on work would center around the process of integrating the simulation environment with a knowledge-based system. The first step might be done in a totally manual fashion, with a single individual exercising the simulator to gain insight about network behavior and then using an expert system building tool to construct a prototype system. This would provide an initial framework in which one could then attempt to link simulation and expert system together. A goal of this effort would be to develop a human-assisted machine learning environment in which knowledge-based systems could be prototyped by interacting, under human guidance, with simulations of the problem domain.

Long-term goals should include the development of communications network simulation tools and techniques for effectively integrating these tools with knowledge based systems. There may be several existing simulation tools which have been developed by other contractors for previous studies, and there will, no doubt, be more in the future. As the machine intelligence technology continues to develop, additional knowledge-based systems are likely to be produced. What will be needed is a common facility to provide a testbed for evaluating these systems in realistic environments.

5. FY87 PLANS

5.1 Demonstrations

The major focus of our work in early FY87 will be preparation for a series of demonstrations to be carried out at Andrews AFB in the February/March 1987 time frame. For these demonstrations we are shipping a Symbolics workstation to Andrews with the expectation of having it up and running there by the end of December 1986. Our plan is to start working with personnel at Andrews so that by the time of the demonstrations they can be proficient enough in the use of ETC to participate in a major way. Ideally, all terminal interactions would be carried out by AF personnel with Lincoln Laboratory involvement limited to explanation and discussion.

In order to carry out a representative demonstration of ETC working at a useful level we need to extend the diagnostic and data entry capabilities beyond those that we showed in the year-end review in September. In particular, we need to continue the fault isolation process beyond the point at which we have effected service restoration, in order to pinpoint the failed component. In many situations this post-restoration fault isolation involves the parallel connection of spare equipment and comparison tests between the behavior of the spare and the unit in question. Much of the software need for post-restoration isolation existed at the time of the annual review but was not shown because the demonstrated procedure stopped when restoration was achieved.

Another diagnostic capability that is needed for the Andrews demonstrations is an ability to handle digital trunk problems. In the

annual review we were limited to faults on individual lines or channels in a trunk circuit. If more than one circuit in a trunk is experiencing problems, the entire trunk is suspect, and a different diagnostic procedure is indicated. A trunk problem can evolve from a problem with an individual circuit (channel), or it can appear as a trunk circuit complaint from an adjacent TCF. The same diagnostic procedure applies in both cases. We need new displays to represent the trunk problem in a suitable form so that the controller can see all of the test points for the trunk multiplexer.

We believe that the above-mentioned extensions to the diagnostic capabilities can be ready in good time for the demonstrations, and moreover that we will be able to deal with additional complaints such as receiving garble on a teletype circuit and excessive transmission problems on a computer-to-computer modem circuit. Ideally, we would also be able to deal with another class of problems caused by broken wires and dirty jacks in the TCF. We are not, however, confident that work in the latter area will be ready to show at the time of the formal demonstrations.

In the area of report generation we expect to have carried the Form 1443 "Trouble and Restoration Record" to a point where it correctly represents the state of the diagnosis/restoration procedure that has been reached by ETC. In the real TCF world the 1443 report is not completed until the circuit is returned to normal operation after repairs have been finished and the circuit has been fully checked out again. We do not plan to include this final phase of outage processing in the demonstrations.

In the area of data entry, we need to extend the CADET program described in Section 2 so that it can handle trunk circuits and new

instances of devices already known in generic terms. Further, CADET must be extended to cause a newly entered circuit to become a permanent part of the data base so that we can expand the database to an interesting size by the time of the demos.

In order to show the potential for direct connection between ETC and the communication equipment that will be available in future more-automated technical control facilities, we plan to connect an AN/FCC-100 time-division multiplexer to ETC using RS-232 ports on the multiplexer and the Symbolics workstation. The connection will be made to a spare FCC-100 at Andrews, and we will be limited to showing that status and alarm information can be sensed by ETC and that the ports on the multiplexer can be configured for a particular use. The latter step is needed when a spare unit is to be placed in service. Unfortunately, the FCC-100 does not allow all of its capabilities to be commanded through the RS-232 port. As a result, we will not be able to invoke the built-in test capabilities of the device. These can only be accessed manually from the front panel controls. We expect that this connection can be demonstrated in February as an independent feature. At that time, this new feature will not be integrated into the circuit diagnosis procedure because the spare FCC-100 is not part of any circuit at Andrews. At a later stage we hope to be able to make a connection to another FCC-100 and demonstrate an ability to sense a failure condition and go directly to a fault isolation/restoration procedure.

5.2 Plans for Extending ETC

There are many different directions in which ETC must be extended in order to approach the breadth of capability that a well-trained tech controller would have. In the preceding section we noted some directions in which we expect to extend capabilities prior to the February demonstrations. In this section we discuss other directions in which work is needed. The total amount of work is more than can be carried out in the upcoming year, and we are not now in position to lay out a detailed plan since we need to get experience with ETC in the Andrews environment to determine whether or not to work toward greater depth or breadth of coverage. In the end we seek both depth and breadth, but there may well be greater interim utility by pursuing one at the expense of the other. For example, we now have a capability to deal with simple problems in data circuits, but we have no capability at all to deal with voice circuit problems. We could leave the data capability at its present level and work on building the voice capability to a comparable level of sophistication. Alternatively, we could continue to develop the data capability while allowing sophistication in the voice area to lag that in the data area. The latter approach could make the system more useful to people at Andrews during the development period, particularly if trainees there were having more trouble handling data circuit problems. We expect to work out this breadth/depth tradeoff in consultation with the expert tech controllers at Andrews once they have had a suitable opportunity to assess the capabilities already in place.

In the data circuit area we have still to add capabilities to handle some simple devices that shift signal levels and standardize timing for teletype signals. We also have a large piece of work to accomplish in handling fault diagnosis on multipoint teletype circuits. (The diagnosis itself should be relatively straightforward since the multipoint circuit can be thought of as a collection of simple circuit segments, but significant changes are needed to deal with the more complex graphical representation of the circuits.) Still more work will be needed to handle systems that combine VFCT channels with modems to accommodate circuits needing a higher data rate than the 75 bits per second offered by a normal VFCT channel. There may well be other special data circuit configurations of which we are not yet aware.

Further work is needed in the database area to remember patches and equipment and line outages across time so that diagnoses of new problems can take account of patches already made, spares already used, etc. New procedures are needed to deal with the checkout of repaired equipment and restored circuits so that the outage reports can be finished off and the database changed to reflect the return to normal status.

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The focus of the FY86 Program in Knowledge-Based Systems Analysis and Control has been development of an Expert System to aid in the operation of the hundreds of military Technical Control Facilities having responsibility for the worldwide network of DoD dedicated circuits. An initial prototype of the Expert System has been created, embodying a substantial proportion of the knowledge involved, and has resulted in improved understanding of Expert Systems techniques and pitfalls for such problems as well as a clear set of goals for completion of the work. *Keywords*

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